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A MANUAL OF

THE PRINCIPLES OF METEOROLOGY

Aurora Borealis.

[*Photographed Midnight, Feb.* 28, 1910, *at Bossekop, Northern Norway, by* Prof. Carl Størmer.]

A MANUAL OF
THE PRINCIPLES OF
METEOROLOGY

BY

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PREFACE

THE object of this Manual is to place before the general reader, in simple language, the author's conception of those conditions obtaining in the atmosphere of the earth which give rise to climate and weather. Of course this limitation debars detailed notice of, or to some extent even mention of, many interesting meteorological phenomena. The purpose of the Manual is thus limited to the treatment of such natural forces as are concerned in the maintenance of the atmosphere's most marked and varying activities.

There are many who contend that Meteorology scarcely deserves to be described as a science. However, it does not follow that, because we are as yet unable to forecast with certainty the weather changes likely to occur even in eight or ten hours' time, this contention is justifiable. In England it is only occasionally possible to forecast the weather for more than ten or twelve hours in advance ; for some of the active agents of change are as yet imperfectly understood, and workers on the subject have to admit inability to account for many phenomena, or even to suggest hypotheses which others might regard worthy of approval.

Although it is true that we are not agreed upon a theory of the winds, or how sudden weather and great climatic changes are brought about, our knowledge of the phenomena presented by the atmosphere abounds in interest. Indeed, although weather changes cannot be accurately predicted, as can eclipses of the sun and moon, there is still a true science of Meteorology which can be studied with profit.

Though the science of Meteorology aims at a study of the conditions obtaining throughout the whole of the atmosphere, the general public views with most interest the conditions obtaining in the lower few thousand feet, and especially the effects produced where the earth's surface is actually in contact with the atmosphere. As a rule the aspect of weather that is most interesting is that of rainfall.

Changes of temperature are generally regarded as being of less importance. The urban dweller and the country dweller naturally have different conceptions as to what is good and what is bad weather. The one delights in the absence of rain, and the continued presence of sunlight ; the other looks for sufficient rain, at proper times to satisfy his crops, and enough heat and sunshine to grow and ripen them.

We can never hope to change the climate of any district appreciably, except to a small extent by irrigation ; but both to the urban dweller and the country dweller it is a distinct advantage to have a reliable forecast of the weather that is likely to obtain in the immediate future. At the present time the reliability of weather forecasts varies greatly in different districts. For example, in Western Europe the cyclones which cause unsettled weather generally come from the Atlantic, and for a knowledge of their movements and peculiarities we depend to a large extent upon the reports received from ships at sea. In many countries, however, the weather changes are either so regular or so slight that little interest is taken in the matter by their inhabitants.

In addition to the variations in the weather which we experience from day to day, there are the changes in rainfall and temperature of a more secular character which have to be considered. Some knowledge in advance of such variations would be very valuable to the agriculturist.

It will be taken for granted that the reader understands what is meant by temperature and pressure, and has some knowledge of such meteorological instruments as the thermometer and barometer. However, such matters as humidity and temperature changes due to the expansion or contraction of the air, will be explained in some detail, as they do not come within the experience of many of us as everyday phenomena.

As yet meteorologists have dealt mainly with the lower atmosphere, attributing all the air movements within five or six miles of the earth's surface to changes in the density of the air at low levels, owing to unequal heating by the sun. However, of recent years, more attention has been paid to

the upper atmosphere, and rather surprising facts have come to light ; facts which render it highly probable that the conditions there are not so equable as was once thought, and have much to do with climate and weather on the earth. Stress will be laid upon this point, for it now appears that the movements of the atmosphere, which we recognise as winds, are largely due, both as regards strength and direction, to the influence of the sun upon the upper as well as the lower atmosphere.

It must be remembered that the air is not a frictionless substance. Any movement set up in it slowly dies down owing to internal friction or to the moving masses of air rubbing against water or land surfaces. On this account each considerable departure from quiet conditions would appear to be due to the action of some powerful but changeable outside agent, such as the sun, the atmosphere itself always tending to assume calm conditions.

The reader will observe that in this Manual more important effects are attributed to the activities of the upper atmosphere than has been the custom in the past. To some extent the conditions obtaining at high levels in the earth's gaseous envelope have to be inferred from what occurs within our reach, but recently many of these inferences have been shown by direct methods of observation to be warranted.

It has always been the view of most students of scientific subjects that the more we know of the laws governing the universe the better we are able to predict future events, and even to control them ; and it is reasonable to hope that as our knowledge of the laws governing the atmosphere improves, weather forecasts will be more reliable and cover longer periods. If this could be achieved more satisfactorily than is now possible, the aviator, the farmer, the sailor and the holiday-maker would benefit.

Before Meteorology may be expected to take its proper place among the sciences that minister to the comforts of man, our knowledge of what is occurring each day over the whole world must be studied in greater detail than is now possible. The Meteorological Office a short time ago made a move in this direction by issuing a daily map or chart of

the conditions obtaining over the whole of Europe, North America and the northern parts of Asia at 7 a.m. on the day of issue. This was a great advance upon previous efforts and a most welcome one. We look for the time, however, when this daily chart will cover the whole Northern Hemisphere, up to the pole: for telegraphic transmission and wireless have largely overcome spatial difficulties. It remains for us in the future to take fuller advantage of present possibilities, especially by installing additional observing stations within the Arctic Circle. Our increasing observations concerning weather peculiarities and climatic changes point more and more to the necessity of studying the meteorological phenomena of such gloomy, frigid, inaccessible and inhospitable localities as the Arctic Regions, the Antarctic Continent, the high plateaux of Asia, etc. Even poets have affirmed that truth is more likely to be found in the dusk of a well than in open daylight!

A full knowledge of what is going on in the polar regions especially during the long winter nights is urgently required. At the present time the public may feel that a wish to know more about Arctic weather conditions is due to idle curiosity, but this emphatically is not the case ; for the two polar areas are paramount among the few great centres of atmospheric activity, and it is necessary, if we are to ascertain the truth, to study them, for they largely regulate the climates of middle latitudes.

The reader who wishes to do any observational work in Meteorology, such as recording daily temperatures, pressures, etc., must consult a practical work on the design and use of meteorological instruments. No attempt will be made in this Manual to deal with technicalities of this description. We are interested more with the deductions that can be drawn from observations that have already been made.

Some consideration will be given to the activities of the sun. From it we receive the light and heat which make our earth habitable. Usually meteorologists have merely taken note of the sun's heat and light rays, which require only a little more than eight minutes to reach us. It is now known, however, that the sun emits electrified material

particles which take days before they enter the earth's atmosphere and affect the magnetic needle. The possibility of such material particles affecting the weather will be carefully considered. This is a subject that can only be treated tentatively. However, as sunspots and certain terrestrial phenomena do change in unison the one with the other, the matter must receive attention. Those who wish to study weather recurrences and weather cycles should consult Sir Richard Gregory's address to the Royal Meteorological Society printed in the Quarterly Journal for April, 1930.

The viewpoint adopted with regard to the great changes of climate which have taken place in the past is that they have been due to causes which are even now in constant operation, and it is considered that no "fresh" influences need be called upon to explain their occurrence. Even now we frequently experience unseasonable weather, some winters and summers being either abnormally dry or wet, or abnormally cold or warm. Such departures from the normal are clearly due to agencies now acting, and no new forces need be postulated to explain them. It is only necessary to assume that the phenomena which cause our present short-period changes of climate, by their rapid fluctuations, have in the past been less changeable, and that those which are responsible for warm conditions have only occasionally been interrupted by those which have caused cold conditions to prevail.

It has not been found possible to avoid all repetition without being ambiguous. However, such has been avoided as much as possible, and when it has been indulged in, it has been for the purpose of making other matters more easily remembered.

My thanks are due to The Astronomer Royal for permission to reproduce the Sunspot photograph, to Prof. Carl Størmer for the photograph of the Aurora Borealis, and to Mr. R. L. Deeley for his generous assistance and for help in the reading of the proofs.

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CONTENTS

POSITION OF PLATES.

A MANUAL OF THE PRINCIPLES OF METEOROLOGY.

CHAPTER I.

INTRODUCTION.

FROM very early times man has taken an interest in weather conditions and speculated upon the causes of daily and seasonal changes. There are few thickly populated areas in which the weather is so constant in its character that it has little interest to the inhabitants. Indeed, much of man's thought is directed towards protecting himself against irregular and seasonal changes of weather. In many countries clothes must be provided to protect him from the cold, and shelters to protect him from rain, and all his outdoor activities are regulated in accordance with the weather variations that occur from day to day. Indeed, it has been said that the atmosphere and its changes are the chief elements in man's physical environment, and the breath of his life. Little wonder that in countries such as our own, where the seasons are well marked and the daily weather changes are also very considerable and irregular, we habitually note and remark upon such conditions. This is more especially the case in the rural districts, where agricultural and other pursuits are at the mercy of weather fluctuations.

There are thus few whose conditions of life are such that they are not interested in weather changes ; most of us speculate as to what each day is likely to bring forth. Shall we don a coat or mackintosh, or carry an umbrella, when we leave home in the morning ? Such matters are often decided without serious thought ; for we have so often considered the question that a decision is come to almost automatically ; but our confidence frequently receives rude shocks. The better

plan, if time permits, is to consult the official weather forecasts which appear in the daily morning papers. Although, however, these official forecasts are made after a close study of the state of the weather over very large areas, they are not considered very reliable for more than twelve hours after issue. Unexpected changes in the weather are apt to occur suddenly and without warning. Indeed, the whole weather conditions over a continent may change drastically within ten or twelve hours.

In this chapter it is proposed to consider some of the salient facts of Meteorology which are to be treated more fully subsequently. It is not suggested that this can be done at present in a completely satisfactory manner, for, in spite of the great advances in knowledge that have been made in recent years, there are few subjects concerning which science can be said to have uttered its last word, and it is not suggested that Meteorology is an exception in this respect. There are many who maintain that Meteorology can scarcely be regarded as a science at all ; but the fact that the results of forecasting weather are somewhat uncertain, and that there are still important unsolved problems to face, should not be regarded as proving the correctness of such a contention. Enough is already known of atmospheric changes and their causes to enable valuable help to be given to practical aviation and the navigation of the seas, and to forecast the immediate changes of weather that are likely to be experienced over land and sea.

However, it must be acknowledged that, although one of the oldest of the sciences, meteorological theory is in many respects backward. This may appear to be a somewhat grave statement to make, but the facts justify it. In the case of most of the sciences, approximately correct explanations of the main phenomena observed can be given. Of Meteorology this cannot be said ; for there is no accepted theory as to the source or sources from which the winds derive their energy, nor are we agreed as to how the climatic changes which the earth has experienced in the past came about. Indeed, many students of Meteorology hardly realise how much our knowledge of the facts is getting ahead of theory. For example, great progress has been made during recent years in our knowledge of climatic changes which have occurred in past ages ; but although this is the case, the fact above stated, that we are not agreed as to the causes of such changes, must be admitted. Scores

of theories have been propounded, but no one of them, or even a combination of some of them, can be regarded as wholly satisfactory.

Although much is known concerning meteorological phenomena, it is evident that unless such phenomena can be accounted for in accordance with scientific principles, it is difficult for the mind to appreciate them properly. If our theories were more complete, there is every reason to believe that apparently contradictory facts would cease to appear so, and Meteorology would rest upon a more scientific basis.

No attempt will be made to show how the views of meteorologists have varied from time to time with regard to the theory of the winds and other matters. These points have been fully discussed by others. However, it can be confidently stated that no general agreement has yet been come to concerning the causes or the actual nature of the circulation of the atmosphere, and it can be shown that the theories generally advanced are quite inadequate to account for the known facts. In the present work it is intended to attempt to show that when the temperature distribution in the *upper* as well as in the lower atmosphere is taken into account, the wind directions can be more satisfactorily accounted for, by supposing that the power which drives them acts largely at high levels in high latitudes and low levels in low latitudes.

Before it is possible to understand atmospheric phenomena it is necessary to have a clear idea concerning the movements of the earth with respect to the sun. This arises from the fact that it is the radiations from the sun which warm the earth and keep the temperature from falling to that of space. Now the rays can strike only one side of the earth at any moment ; but as the earth rotates, successive portions of its surface feel the warming effect. When the axis around which the earth rotates is at right-angles to the sun's rays, then during each revolution, except actually at the poles, all parts receive some heat, and we shall see that the amount of heat received per square mile becomes less and less as the poles are approached. The result is, that, except near the poles, each portion of the surface enjoys the heat and light rays of the sun for twelve hours, and during the other twelve hours receives no such rays whatever. In these circumstances the earth's surface at sunrise begins to get warm, reaches its highest temperature after midday, and then cools down as night approaches, continuing to do so almost until the sun rises next morning. It

will be seen from this how important the length of the day is with respect to climate. For present purposes the earth may be regarded as revolving on its axis a little more than 365 times each year; but if there were fewer days in the year, the dark and light periods would be of greater duration, the day temperatures would be higher and the night temperatures lower, and morning frosts more prevalent.

However, the earth's axis is not always at right-angles to the plane of its orbit round the sun, the consequence being that twice only during each year the days and nights are of equal length, and in a year there is continuous sunlight for six months at each pole and six months of night. Between these extremes (the poles) the conditions of lighting are transition ones. As this matter is of the greatest importance in Meteorology, it is necessary to consider it in some detail.

Were it not for the presence of an atmosphere and oceans, and the fact that air can take up a considerable quantity of water in the form of an invisible vapour, the changes of temperature between night and day would be greater than they are. But fortunately the atmosphere and oceans absorb and retain the heat of the sun and prevent the earth's surface from being unduly warmed. They also tend to check the loss of heat during the night. In this way the atmosphere and oceans prevent undue fluctuations of temperature in all latitudes.

Were the length of our day much greater than it is, the low temperatures before sunrise would check vegetation in the spring and prevent many plants from ripening their seeds in the late summer and autumn.

The earth is a slightly oblate spheroid of matter, its diameter being 26 miles less from pole to pole than across the equator, and its surface is at such a temperature that the greater part of it is able to support life. Although only a small fraction of its weight consists of water and air, together these two substances envelop the solid earth completely. Water, being the heavier of the two, sinks into the hollows in the solid surface. Upon the water, and the land surfaces which are too elevated to be submerged, rests the atmosphere. Both upon land and sea the air presses with a force dependent upon its weight, this weight resulting from the force of gravity acting upon it. The atmosphere is largely transparent to most of the rays of the sun, light and heat rays penetrating it and striking the earth's surface. However, many phenomena of the upper atmosphere render it very probable that the sun radiates

material particles, which are deflected and captured by the earth's magnetic field, and are finally stopped by the upper atmosphere in high latitudes, where they raise the temperature of the air. The possible heating of the atmosphere in this way has hitherto received little consideration.

It is not intended in this work to deal with the many and interesting sky phenomena which the shepherd and farmer rely upon as a basis for foretelling weather changes ; for the signs relied upon are not the same in all districts, and the significance attributed to many of them is without any scientific basis.

As already indicated, Meteorology as a science is under the disadvantage of not possessing any generally accepted theory accounting for the general circulation of the atmosphere. As a matter of fact it is not merely the major movements of the air which are unexplained ; for even the source from which comparatively small cyclones derive their energy is considered uncertain, and there is no valid explanation for the barometric pressure obtaining over the greater part of the globe being what it is. In this respect Meteorology is in the condition many of the other sciences were and some still are. We are in the position of having an immense amount of detail to grasp, but are without a knowledge of the principles which would make the facts easily understood and remembered. It may be that a more complete knowledge of the main principles of the science would enable us not only to understand how and why the atmosphere flows and acts as it does, but also enable us to foretell well in advance what changes are likely to take place in its movements, and thus improve our methods of forecasting.

As early as the fifth century B.C. it was recognised that wind is a " flowing of the air." We thus have at this early period a recognition of the fact that we live in and breathe a transparent gas which envelops the earth and is often in motion. However, even such a genius as Aristotle held very vague notions concerning the atmosphere ; but if we omit most of his detailed conceptions regarding it, his tripartite division bears some resemblance to modern views. Thus he regarded meteors and comets as " exhalations " ascending from the earth and becoming heated and incandescent on reaching the upper " region " of fire (the heavens). Aristotle's lower " region " was that portion of the atmosphere which is very near the earth, and in which plants and animals live. Above this was his intermediate " region " of intense cold. His upper or third " region "

was supposed to be intensely hot. We now recognise that above the cold region there is a warm if not intensely hot region. Strangely enough one method now used for roughly ascertaining the temperature of this upper region depends upon the fact that meteors become incandescent on striking it ; but Aristotle imagined that the meteors ascended from the earth's surface and became incandescent on reaching his upper hot layer. We now know that the meteors come from space, and become incandescent when they strike this upper warm portion of the atmosphere. However, when facts were wanting, Aristotle filled in many imaginary details of a startling nature.

We now divide the atmosphere into two regions. In the lower portion, called the *troposphere*, the temperature falls rapidly as we rise. At a certain height, which varies from time to time, this fall of temperature ceases, this level being called the *tropopause*. Above it the temperature remains stationary or rises again with increasing height. This upper region is called the *stratosphere*, and at a very great height is probably as warm as the troposphere is at the earth's surface.

Stress has been laid upon Aristotle's three "regions" because three such regions are now known to exist. Hitherto attention has been paid almost wholly to the lower region in which we live, theories of meteorological phenomena being based almost wholly upon its activities. Until recently such theories could not be based upon other considerations, for very little indeed was known of conditions obtaining above heights reached by manned balloons or accessible mountain summits. But we now have good reasons for believing that in high latitudes the pressure phenomena near the earth's surface are largely the result of what is going on at greater heights.

The exact thickness of the atmosphere is not known. Indeed the atmosphere may possibly be continuous with space, which is not quite free from matter, and therefore have no definite upper surface. The likelihood of this being so is based on the high temperature of the air at great heights. Some light is thrown on the question of the thickness of the atmosphere by the aurora, which is probably caused by the bombardment of the air by electrically charged radiation from the sun. The upper limit of the aurora is generally about 400 kilometres above the earth's surface, where it first becomes visible, and its lower limit of visibility is about 90 kilometres. The thickness calculated from the observation of meteors shows that there is warm gas as high

as 300 kilometres, whilst the thickness required to produce twilight is about 64 kilometres.

Although not as ponderable as water, the atmosphere in which we live is quite recognisable by our ordinary senses. When we move quickly through it, either on foot or in a motor car, it offers very marked resistance to our progress. Though wind is air in motion with any degree of velocity, when the air is at rest and we move through it, the phenomena we experience are exactly the same as those we experience in windy weather. Air is really a mixture of several kinds of matter in the gaseous state, all of which become liquid or solid at very low temperatures. All these constituents are very easily compressed or expanded. If we immerse the neck of a bottle in a vessel of water, the water will not enter, but if we force the bottle much below the surface of the water it will be seen that the air has been compressed a little, and some water has risen into the bottle neck. Air can be "sucked" out of a vessel by means of a pump or forced by the same means into any vessel in very considerable quantities. When we blow up the tyre of a motor car, we prove this, and the pressure of the air in the tyre is greater the more air we force in. Conversely, as the air is withdrawn from a vessel the pressure in the vessel falls, and when all the air has been drawn out a perfect vacuum is formed. Measurements show that under these conditions of reduced pressure the air outside is exerting a pressure upon the containing walls. We conclude as the result of experiment that the atmosphere in which we live has a pressure of about fifteen pounds per square inch at the earth's surface.

By weighing a vessel when it is full of air, and then weighing again when all the air has been removed, we find that the vessel has decreased in weight. Air, therefore, possesses weight like other kinds of matter. A cork thrown into water swims on the surface. This is because cork is lighter than water. The gas we use in our gas stoves is lighter than air; a light rubber balloon filled with stove gas is lighter, volume for volume, than the surrounding air, and when it is released it rises. As it does so the gas within the rubber envelope expands, the balloon growing larger as it gets higher and higher and in the end bursting—a very important fact which deserves close consideration.

Meteorologists measure the pressure of the atmosphere by means of the barometer. In the mercury instrument the heavy liquid metal mercury is placed in a long tube, say three feet long. The open end is then dipped into a

vessel full of mercury, in such a way as not to admit air to the tube, and when more than about thirty inches of the tube stand out of the liquid it will be found that the mercury does not fill the tube, there being a vacuum in the upper empty portion. Now it is the pressure of the atmosphere upon the surface of the mercury resting in the vessel that forces the mercury up the tube, and we conclude that the weight of a column of air of the same diameter as the inside of the tube and reaching up to the top of the atmosphere, is the same as that of the thirty inches or so of mercury in the tube. This weight or pressure is found to change from hour to hour and day to day. To make quite certain that the rise of the mercury is due to the weight of the column of atmospheric air, the instrument has been taken to the top of a mountain, where the height and weight of the atmosphere above the instrument were less, it being found that the column of mercury was then shorter. Experiment has also shown that the higher the temperature of the air the lighter the air is. Owing to the fact that as we rise the air gets more tenuous, and the pressure decreases, the atmosphere is much thicker than it would be if it were not capable of practically indefinite expansion. Of course when the thickness of the gaseous envelope of the earth (the atmosphere) is compared with the diameter of the earth it is found comparatively to be very thin indeed. One half of the weight of the atmosphere is below the four miles level, and taking a billiard ball as being two inches in diameter, a bit of tissue paper, one thousand sheets of which would be required to make an inch, pasted on its surface would represent more than this half of the atmosphere. At a height of seven miles, three parts out of four of the mass of the air have been passed through, whilst at a height of eleven miles we have pierced nine parts out of ten of the mass. The lighting up of meteors by friction with the air often occurs at heights of one hundred and eighty miles, so it is clear that even at these high levels air of extreme tenuity still exists.

It has been assumed that the temperature of the upper atmosphere is very evenly distributed, and that on this account there are no vertical movements in the stratosphere ; for, if a mass of air should rise a little at one place and a similar-sized mass fall at another, the one would cool by expansion and the other become heated by compression, the varying densities thus produced preventing further displacement—indeed the masses of air should return to their former positions. However if the radiations from

the sun produce irregular horizontal heating either in the troposphere or stratosphere, vertical and horizontal currents will be set up so as to make the temperatures equal again at similar levels. That winds in the stratosphere exist has been proved. Some meteors when they graze the upper atmosphere leave luminous streaks behind them called bolides. At first these streaks appear regularly curved. They move rapidly, however, as they are carried along by the upper winds, and in course of time become bent and broken.

In an introductory reference to the most marked features of the atmosphere, note must be taken of the effects produced by the water, land, snow or ice, upon which the atmosphere rests. About one quarter of the surface of the earth is land, the other part being covered by water. Except when the winds are very light the air moves in gusts and eddies, and the air layer in contact with the surface upon which the atmosphere rests is constantly being changed. Owing to this, and the fact that the density of the air is decreased by heating, vertical movements are set up. Over heated land this results in the production of a low warm layer of air. Similar results follow over the warm tropical seas. The warming effect of the land and ice- and snow-covered areas in high latitudes is, however, much less than in the tropics. All land and water surfaces are warmed either directly or indirectly by the sun, and the air temperature at the earth's surface, even in the Arctic and Antarctic regions, is much greater than at the top of the troposphere (lower atmosphere). The average of a large number of observations shows that the mean temperature difference between the surface air in middle latitudes and that at the top of the lower atmosphere (troposphere) is about 117° F., but varies considerably from time to time.

It is as a result of the passage of the air over the great oceans and seas that the most remarkable consequences follow. Water gives off vapour which mingles with the air (this vapour, being transparent, is quite invisible). The amount that can be absorbed by the atmosphere is greater the higher the temperature, and when the air becomes saturated with it at high temperatures, any cooling of the mixture makes it imperative that a portion, depending upon the fall of temperature, shall again appear as water. This is thrown down in the air as minute drops, forming mist, fog and cloud. When air charged with moisture comes in contact with cold surfaces, some of the moisture condenses upon them and wets them. Inspired air, for example,

becomes warmed and saturated with moisture in the lungs, and when we breathe upon a cold looking-glass the surface is dimmed by deposited moisture. In clouds, when the drops become large they fall as rain, either over the sea or land. In this way large areas of land are kept moist and the growth of vegetation is rendered possible. Were it not for this ability of water to vaporise and mix with the air and be thrown down again, life would only be possible in the seas and oceans, the land areas then being sandy wastes traversed by dust storms.

Owing to the fall of temperature as we rise through the atmosphere, there is very little water vapour in the air above the four miles which account for half the mass of the atmosphere. The precipitation of water in the form of snow and ice on mountains, like Everest, which reach a height of five miles is generally not large. Now it is certain that the temperature gradients in the lower four miles of the atmosphere do not give rise to differences of density which are capable of accounting for the atmospheric circulation as we know it from a study of the winds. The only point that can be made here, however, is that air movements are due to cold heavy air falling and warm light air rising.

Though the deep-seated portions of the earth's crust are at high temperatures, owing to the badly-conducting nature of the rocks, this internal heat has no effect upon climate. Indeed the rise of temperature as we travel from the surface downwards through the rocks is only about 1° F. for every 64 feet or thereabouts of descent (the gradient of temperature varies somewhat from place to place). It has been calculated that the heat reaching the surface from below, owing to this temperature gradient, would melt a layer of ice only 0·64 centimetre thick per annum.

As we are only about ninety-three million miles from the sun, a short distance astronomically, at this distance its rays are very powerful, and the earth owing to its atmosphere and the presence of water having the intense heat of the sun mitigated during the day and the loss of heat during the night checked, for all practical purposes the climate of the earth is entirely due to warming by the sun in one way or other, combined with the reservoir effect of the atmosphere and oceans.

The experience of most of us has brought to our notice the cooling effect of our long winter nights. In the tropics, where variation in the length of the day is almost non-existent, seasonal and daily changes of temperature generally are much less pronounced than they are in high latitudes

(but it frequently occurs that seasonal changes in low latitudes are marked by wet and dry periods). Such being the case, the meteorologist must take note of the movements of the earth with regard to the sun, so that he may understand the cause of the variations in the lengths of the days, and the resulting effects on climate.

The four principal factors which determine the amount of heat absorbed by different portions of the earth's surface are:—

(1) The solar output of radiated energy, which warms the atmosphere at almost all levels and also the earth's surface.
(2) The earth's varying distance from the sun.
(3) The inclination of the rays when they reach the earth.
(4) The heat retained by the earth, oceans and atmosphere.

The amount of heat and light radiated by the sun is constantly varying within narrow limits. The small changes above and below the mean are, in some cases, somewhat rapid, and in others are long-period ones. It has been calculated that a long-continued change of solar temperature which would alter the heat radiated by the sun by 2 per cent., would alter the earth's effective temperature by 1·25° C. When the sun is nearest the earth its power is about 6·6 per cent. greater than when it is farthest away, and this would vary the temperature roughly by 4° C. The varying height of the sun above the horizon is a much more important matter, as also is the varying length of the day and night due to latitude—it is to these two factors that we owe the great difference between polar and equatorial climates. This difference would be much more pronounced if it were not for the fact that a great deal of heat is stored up in the air, earth and oceans, and much of it is carried from warm to cooler regions by the winds, ocean currents or drifts.

The periodic distribution of insolation (warming by the sun's rays) is due to two main causes:—(1) the rotation of the earth on its axis; (2) the inclination of the earth's axis to the plane of its orbit round the sun. Omitting consideration for the moment of the sun's distance and earth's atmosphere, the quantity of heat that falls upon any portion of the earth's surface each day depends upon the height of the sun above the horizon and the duration of sunlight.

Fig. 1 shows the earth's orbit in plan viewed from the north, the sun being in the centre, and the earth in four of its positions during the year. The North Pole, it will be noticed in the figure, is not central with the disc of the earth. The polar axis is inclined at an angle of $23\frac{1}{2}$ degrees. On September 23 and March 21 day and night are equal in all latitudes. These are the *equinoxes*. On December 22

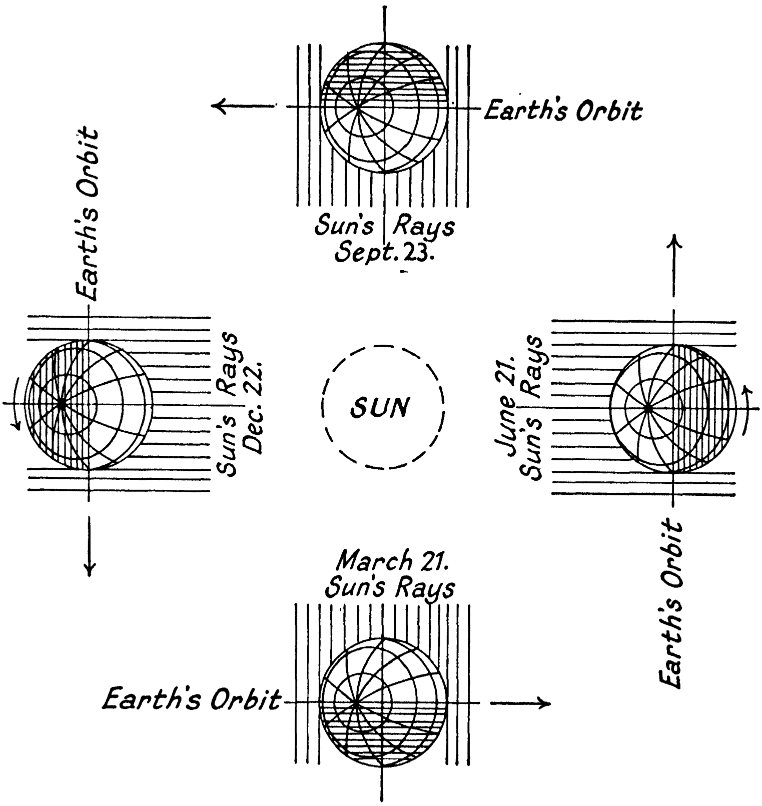


Fig. 1.—Showing Earth's Orbit with Earth in its Positions at Equinoxes and Solstices.

and June 21 we have the *winter* and *summer solstices*, and on December 22, within a distance of $23\frac{1}{2}$ degrees from the pole, the sun does not rise above the horizon at any time during the day. The Arctic and Antarctic Circles are $23\frac{1}{2}$ degrees from the poles, and are thus determined by the earth's inclination to the plane of the ecliptic, *i.e.* the plane of the earth's orbit round the sun. Compared with its distance from the sun, the earth is so small in diameter that to make the distances and diameters agree as regards scale the earth would have to be shown in Fig. 1 as being

about 600 feet from the sun. On this account the lines on the plan indicating the orbit of the earth are shown straight and the light rays parallel. The disc of the sun has been much reduced in size, and the four figures of the earth have been drawn together so as to get them on the page.

In the winter in middle latitudes the sun rises in the south-east, does not get high in the sky at midday and sets in the south-west. During the night our luminary is far below the northern horizon, twilight is short, and the nights are long and dark. At the equinoxes, *i.e.* when day and night are of equal length, the sun rises in the east and sets in the west, its height above the horizon at midday varying with the latitude. On midsummer day the sun rises in the north-east, is high in the sky at midday, and

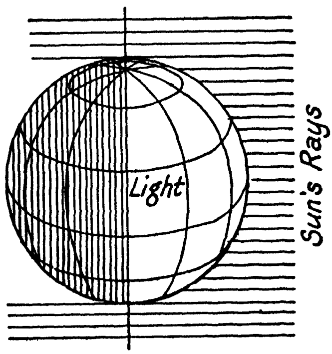


Fig. 2.—Showing Illumination of Earth at Equinoxes.

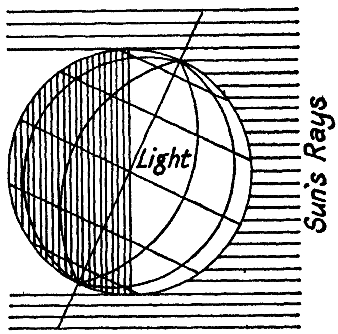


Fig. 3.—Showing Illumination of Earth at Northern Summer Solstice.

sets in the north-west. In moderately high latitudes in summer, twilight is prolonged, the sun being so little below the northern horizon that its light can be seen in the north at midnight. When we get north of the Arctic Circle on June 21, the sun itself is visible at midnight.

The position of the earth with regard to the sun on March 21 and September 23 is as shown in Fig. 2, and on June 21 as in Fig. 3. If it were not for the inclination of the axis of rotation, the day would have the same length all over the earth at all times, there would be no seasons, and at the poles the sun would constantly circle around the horizon, being only just visible.

As regards the seasons, the principal effect of the inclination of the earth's axis to the plane of its orbit is to cause the sun to pass twice each year across the equator, and to march about 23·5° north and south of it each year. When the sun, for example, is over the Tropic of Cancer, it is

summer in the Northern Hemisphere, and when over the Tropic of Capricorn, it is summer in the Southern Hemisphere. Indeed this march of the sun north and south of the equator, due to the inclination of the earth's axis to the ecliptic, has most important consequences and must be borne steadily in mind. The varying length of the polar days and nights is due to it. It gives long periods of daylight in summer to high latitudes, and thus increases the habitable area of the earth, for the land can produce crops during the summer in rather high latitudes, and lie fallow during the cold of winter.

When the sun is overhead, any beam of heat and light rays strikes the earth's surface vertically and the maximum heating effect is produced. When, however, the sun is low down on the horizon, a beam of equal cross-section is spread over a much larger area of the earth's surface and the heating effect is much reduced; and when the sun is actually upon the horizon the rays do not fall on the surface at all, and the heating effect would be nil were it not for the presence of the atmosphere, which intercepts some of the heat even under these conditions. This is illustrated in Fig. 4. Here three beams of sunlight (A), (B) and (C), all of the same power and sectional area, impinge upon the earth. Although, however, they are of the same power, the areas of the earth's surface they warm grow larger as we move from (A) to (C), the area heated becoming greater the higher the latitude. The part of the lower atmosphere which plays any considerable part in climatic changes is very thin indeed when compared with the earth's diameter, or with the whole thickness of the atmosphere. On this account for meteorological purposes it is necessary to regard only the earth's surface and atmosphere as being concerned in intercepting the sun's heat, there being practically no heat coming out from the earth's hot interior.

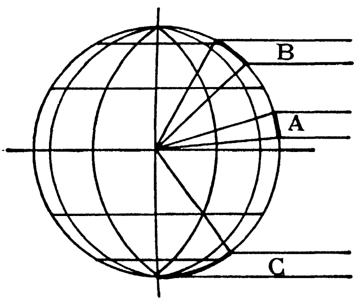


Fig. 4.—Variation of Sun's Heating Effect with Latitude.

Although the sun does not rise above the horizon along the Arctic and Antarctic Circles, lat. 66½°, at midwinter and at the poles there are six months day and six months night, there is always sunlight at no great height over the poles above the shadow the earth throws into space. The

cone of darkness over the poles is that part of the earth's shadow which (relative to the earth) exists throughout the whole midwinter's day, and is very obtuse at its apex. Fig. 5 shows this midwinter cone of continuous darkness. Above the North Pole on December 22, at a height of 400 miles, the sun is visible throughout the 24 hours. This conical form of the shadow does not very appreciably affect the length of the day, as far as the mass of the atmosphere is concerned which lies inside the Arctic Circle ; for the thick line indicating the earth's surface is about as thick as the lower atmosphere (troposphere). It is only when the higher levels of the upper atmosphere (stratosphere) are reached that the length of the polar night is much reduced. The mean pressure of the atmosphere at the earth's surface is about 1013 millibars at the latitude of the British Isles ; but at a height of 25 miles it is under 5 millibars, so that the vast

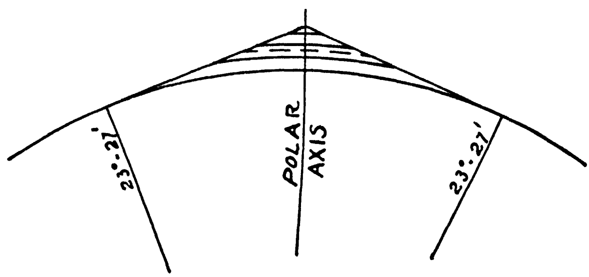


Fig. 5.—Polar Cone of Darkness at Solstices.

mass of the air is close to the base of the dark cone. The full lines in the dark cone are one hundred miles apart.

An intensive study of the lower region of the atmosphere has not furnished us with facts which can explain all that occurs there. Indeed many of the phenomena of this lower region seem to be in direct contradiction the one with the other, and it is becoming more and more clear that the atmosphere must be dealt with as a whole if we are to formulate principles or laws which will bind together our less general theories.

Meteorologists, as already stated, find it most convenient to divide the atmosphere into two portions. The lower atmosphere, called the troposphere, extends from the earth's surface to the level where the temperature is lowest, this level being known as the tropopause, and an upper atmosphere, known as the stratosphere extends from the coldest stratum up to where the air meets space. Whether at this height there is a definite limit to the atmosphere is

not clear as yet. At one time the air at this level was regarded as being intensely cold, but we now know that it is warm, and the velocities of the molecules may be such that many of them can pass into space, other molecules from space joining our atmosphere. There are many meteorological and geological problems no really satisfactory explanations of which have yet been given, problems which seem to defy solution as long as the stratosphere is regarded as practically inactive. However, it is now coming to be recognised that even at very great heights there are unsuspected phenomena of great interest and importance. Many of these it is impossible to discuss here, for they do not bear upon the main principles of the science of Meteorology.

Our knowledge of Aristotle's "cold region" has been obtained by sending up small rubber balloons to which an instrument is attached which registers the temperature and pressure of the air as the balloon rises and falls again. The balloon has a diameter when filled with hydrogen gas of about four feet. As it rises the gas within expands and the balloon swells until it bursts and falls. Such balloons sometimes reach heights of twelve miles or more. Knowing the barometric pressures and the temperatures recorded by the instrument as it rises and falls, the variations of temperature with height can be calculated. Large numbers of such registering balloons, with recording instruments attached, have been sent up at different latitudes, and a moderately good idea of the temperature of the troposphere and lower portion of the stratosphere has thus been obtained. The region of low pressure at the centre of deep cyclones, however, has not been well explored by balloons of the registering type ; for the weather is rough there, and registering balloons are difficult to send up and recover.

It has been stated already that the movements of the air must result from temperature differences. A mass of warm air surrounded by cold air will rise vertically and the cold surrounding air will spread beneath it. The heated gases from a fire rise up the chimney, for example, and draw fresh cool air into the room. Similarly the hot gases from a bonfire rise and carry sparks up with them. In the case of the atmosphere the heating takes place over much larger spaces, and we can point to large areas where the heating disturbs the air much as it does in the case of the firegrate and bonfire. The effect, for example, on the sea-shore in the tropics is very marked. During the day the land is heated and during the night it cools down considerably. The early mornings are hot and the inhabitants of the

sea-shore wait with impatience for the coming of the cool sea breeze, which usually sets in about ten o'clock. The air over the land, especially if there are hills near, becomes heated and rises, its place being taken by air which has been cooled over the sea during the night, and the oppressive morning heat is dissipated. Towards sunset the sea breeze dies down and the close and hot land breeze sets in again. This alternation of winds from the sea and from the land is in many tropical countries extremely regular. Many of the more steady and persistent winds of the earth, such as the Trade Winds, can be traced to this direct heating of the lower portion of the troposphere by the sun. Similar results are produced in high plateau regions.

Land breezes are more marked in low than in high latitudes, and occur less frequently during winter than summer. The atmosphere is seldom affected in this way, except as regards the Trade Winds, to heights of more than 600 metres, or distances more than thirty kilometres inland. In some localities, during summer especially, there is a continuous sea breeze lighter at night than during the day. It affects the atmosphere to a much greater height, and travels farther inland.

At one time it was considered that all the general winds of the earth were caused in this way, but the information obtained concerning the actual distribution of temperature in the lower atmosphere does not support the view. In most instances winds travel in curved paths, around areas of low pressure called depressions (or cyclones), and it was thought that near the earth's surface the central air of the cyclone was always warmer than that at a distance, and that the air movement was always due to the rising of the buoyant warm air at low levels. However, self-registering balloons, and temperatures taken on high mountains, show that the centre of a cyclone at low levels is cool, not warm, as compared with its surroundings. A foreign writer demonstrated in 1888 that in very many cases the temperatures in the interiors of cyclones and anticyclones up to considerable altitudes are such that it is impossible to regard the existence of these "weather centres" as being due to the varying temperature and density of the lower air, and he remarks that one is inevitably led to explain them as a result of the influence of the general circulation. However, this view is quite untenable, for the general circulation is itself cyclonic. In this work it will be considered that the atmosphere over the centres of cyclones at heights well above our mountain ranges is warm as compared with the surrounding

air at similar levels, and that it is the low density of this upper air, largely due to the depression of the tropopause, which gives rise to the low pressure and air movements in cyclones.

It has been contended that the changes of temperature, and therefore of density, due to the expansion or compression of rising or falling air, are such as to prevent vertical movements, especially in the upper atmosphere. This contention is certainly not applicable to the stratosphere, for such movements as occur there are those necessary to bring about the required regularity of temperature and pressure where these have been disturbed by irregular heating. This effect is not very marked except in low latitudes in the lower atmosphere. Indeed the cold and warm areas are often arranged vertically in such a way as to show that they are slightly opposing rather than assisting the formation of cyclones.

In the lower atmosphere the effect of rising and falling air currents, due to temperature variations, is to bring it approximately into a condition of what is known as "convective equilibrium," that is, a condition in which the temperature falls steadily at a certain rate as we rise. When once this steady condition is reached, vertical as well as horizontal air currents are free to circulate, for changes of temperature due to rising or falling currents then occur in such a manner as not to vary the vertical temperature distribution. The vertical temperature gradient required to produce this result also depends upon the amount of water vapour the air contains ; but as the matter will have to be discussed fully later, it need not be more than noticed here. However, if the vertical temperature gradient be such that with increasing height the air actually gets warmer than it would do by convection, then vertical currents would be impossible unless outside influences were at work.

In both cyclones and anticyclones, the winds blow in a very definite manner, the law expressing their movements being of a very simple character. If we stand with the wind at our backs the low pressure area is to our left and the high pressure area to our right in the Northern Hemisphere. In the Southern Hemisphere the high pressure is to the left and the low pressure to the right. This is explained fully later. Near the earth's surface the wind at low levels generally blows spirally *towards* the centre of low pressure, but at high levels in the troposphere whilst the direction of movement around the centre is the same as at low levels, it is spirally from the centre. On this account the air which

at low levels flows towards the centre of the depression moves outwards again almost wholly in the upper portion of the troposphere.

When the cyclone is stationary with regard to the earth's surface, the problem of the direction of the winds therein is not a very difficult one ; but when the whole cyclone is moving with respect to the earth's surface, or the general winds of the stratosphere do not move in the same direction as those of the troposphere, very complex wind conditions may obtain.

The foregoing conception of the direction of air movement in a cyclone is generally known as Buys Ballot's Law, and it should be committed to memory.

We shall see that the peculiar distribution of land and water on the earth has a very marked effect upon the distribution of temperature and pressure. Of the numerous theories that have been formed to explain the present distribution of land and water, no one of them can be said to be quite satisfactory. However, any generalisation which serves to link together the main peculiarities of earth surface structure, although it may be for many reasons untenable as an explanation of the facts, is useful as a means of giving a mental picture of the phenomena. The tetrahedral theory is such an one. It is based upon the supposition that the earth's crust, at some early period in the earth's history, got too large for the interior, or rather the interior got too small for the crust, which wrinkled in consequence. The main lines of upthrust are supposed to have taken place in such directions that the earth's surface became roughly divided into four slightly depressed areas, divided from each other by more or less high ridges of land, thus giving the four triangular areas of the tetrahedron. The lines of disturbance and elevation thus produced are, by this theory, regarded as having persisted, the continents grouping themselves about the coigns and edges.

Fig. 6 is a map of the earth on Mercator's projection showing the distribution of the continents and oceans. On it are drawn the lines dividing the surface of the earth into the four triangular portions of the tetrahedron. These are, of course, distorted by the method of projection adopted when drawing the map so as to show the quarter portions of the curved surface of a sphere on a flat surface. It is clear that the land areas do not group themselves about the coigns and ridges at all satisfactorily. However, if they were so arranged, each continent would have an ocean opposing it on the other side of the earth.

Now it is a strange fact that the positions of the continents, although they are not in good agreement with the requirements of the tetrahedral theory, are accurately arranged so that all the large land areas have large water areas at their antipodes. This will be seen by consulting Fig. 7.

In Fig. 7 the distribution of land and sea in the two hemispheres is represented in such a way that every point in the Northern Hemisphere has its antipode superposed upon it. The land in the Northern Hemisphere is indicated by vertical hatching, and the land in the Southern Hemisphere

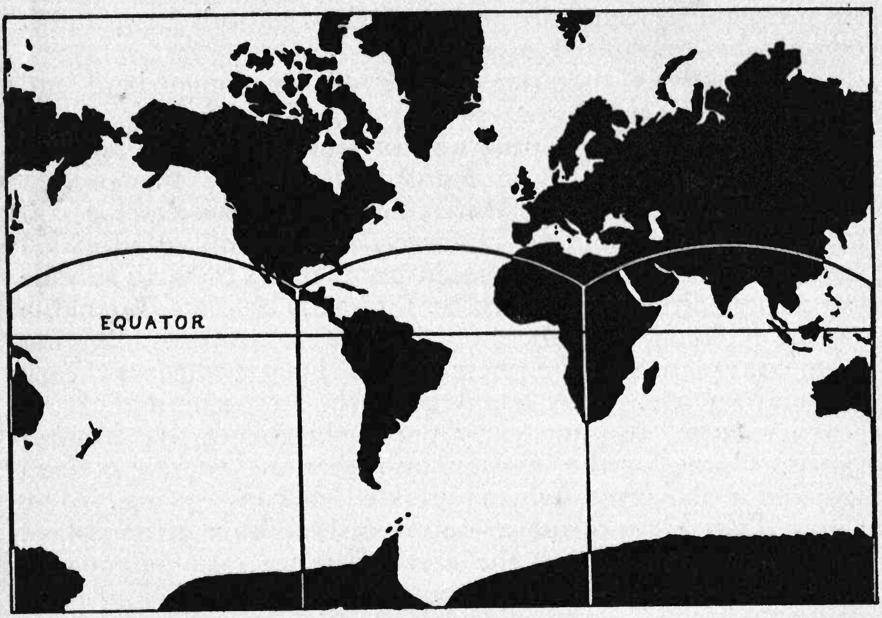


Fig. 6.—Continents and Oceans and Tetrahedral Theory.

by horizontal hatching. The southern part of South America is the only continental land of the Southern Hemisphere which has a continent as its antipode in the Northern Hemisphere.

Another theory, that of Wagener, is based on the supposition that all the land once formed one large continent which has broken up, and the fragments have drifted into their present positions.

The first theory makes the positions of the continents the result of cooling and compression so as to form a tetrahedral pattern on the earth, whilst the other floats the continents into such positions that they are actually antipodal to the oceans.

Neither of these theories can be considered satisfactory, but from the point of view of the meteorologist the most interesting feature of the actual distribution of the land is, that at the North Pole we have an ocean surrounded by land, whereas at the South Pole we have a continent surrounded by water, and any difference in the flow of the winds between the Northern and Southern Hemispheres must result from this difference.

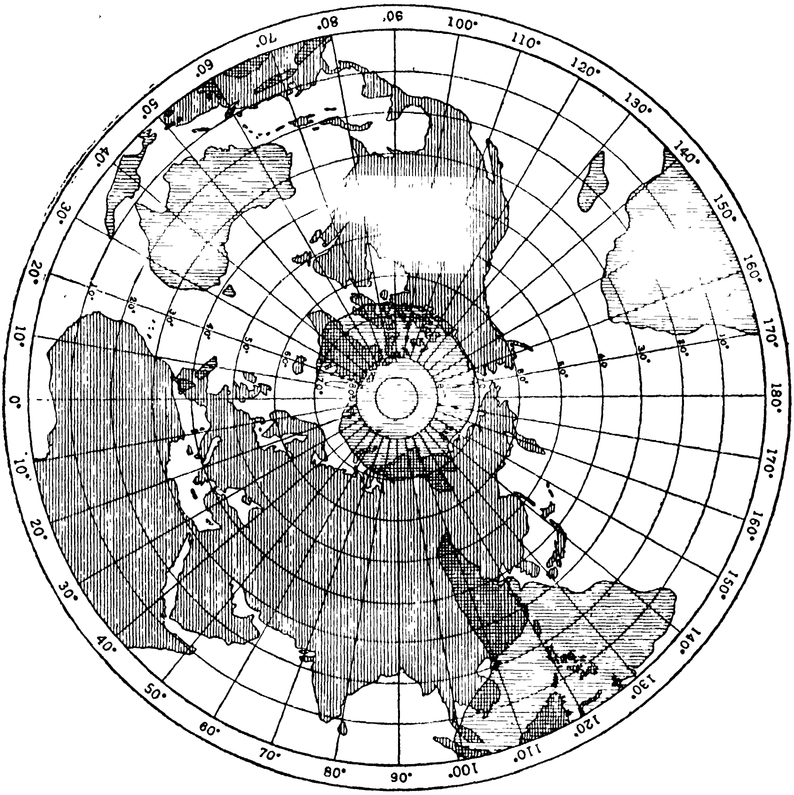


Fig. 7.—Showing Antipodal Positions of Continents and Oceans.
(From "*Nature*.")

By a study of the rock masses forming the crust of the earth we have learned much concerning past history. We all know that during wet weather the streams and rivers become swollen into torrents and carry along with them to pools, lakes and seas vast quantities of vegetation, the bodies of animals and insects, together with gravel, sand and mud. In this way in many districts as much as a foot or more of the surface is carried into the sea in a thousand years and there forms beds of sandstone, shale, etc. in which

can be seen the impressions or actual remains of the living things of the time.

As a matter of fact a large proportion of the upper crust of the earth has been formed in this way, and by examining the traces of the organisms it contains we are able to ascertain what the former occupants of the earth were like. The rocks not only preserve in a form suitable for examination the former living things of the earth, but they preserve also the ripple marks on the old sea-shores, the small pitted impressions where rain drops fell, and the footprints of animals.

In addition to such records of showers of rain, ripple marks on sea-shores, and plants and animals, we also have ample evidence of the existence in the past of ice and glaciers at several periods.

In the Arctic and Antarctic regions recent glacial deposits both on land and in the sea contain vast quantities of rock debris, often consisting of fine mud with embedded stones. These stones are often beautifully polished and striated. The glaciers which flow down the valleys as vast rivers are studded with stones stuck in their lower surfaces, and as the glacier slowly slips over its bed these stones have more or less flat, polished and striated surfaces formed upon them, and they polish the floor over which they move when it is rocky. This phenomenon may be seen in the Alps and frigid localities at the present day.

An examination of the records of the rocks of the world shows that glaciers have existed where the climate is now temperate or even tropical, and that where the climate is now frigid tropical conditions once prevailed. Geology, that is, the study of the rocks, shows us that there is no ground for the supposition that the present climatic conditions of the earth are normal ones. During the earth's two thousand million years of existence, during which life in one form or other has flourished on its surface, there have been great changes in the distribution of land and water, the average height of the land above the sea has been subject to great changes, and remarkable variations in the climate have occurred. We do not know, however, if continents and oceans have always been antipodal.

We are familiar with the conditions of climate which the earth now enjoys. Tropical climates characterise wide belts on each side of the equator, whilst as we approach the poles the climate becomes colder and colder in an irregular manner until the frigid polar areas are reached. The densely populated areas all lie in the temperate and tropical zones,

and it is a remarkable fact that during man's evolution very great oscillations of climate have occurred probably during the greater portion of the time. When the subject comes up for more detailed consideration it will be seen that about one million years ago there were no great glaciers or ice sheets in the Arctic regions. Indeed a study of the rocks tells us that throughout geological time the poles have been frigid only for short intervals now and then, such cold intervals not being persistent. About a million years ago the temperature of the polar areas began to fall and glaciers grew and spread until they covered large areas of the American, European and Asiatic Continents. The ice from the Scandinavian Peninsula, reinforced by flows from Scotland, Northern England and Wales, reached as far as the Thames, the ice from the Swiss Alps covered the area now occupied by Lake Geneva and passed down the valley of the Rhone as far as Lyons. In America the whole of Canada was buried and ice fields extended as far as St. Louis. Man's ancestors at this time were a very primitive race. This cold period did not last very long, however, and it was succeeded by a warm interval of considerable duration. This warm period was followed by at least three major and one or more minor cold epochs separated by warmer intervals. Compared with the average climatic conditions of geological time, even the present conditions must be considered as unusually cold, for before the appearance of the first cold epoch we have mentioned, Spitzbergen, Iceland and other ice-covered areas enjoyed semi-tropical climates and supported an abundant vegetation.

The evolution of man took place during the times these great oscillations of climate occurred. He retreated as the frost and ice advanced and advanced again as the ice retreated. It may be that he had to fight his way south against his fellow men, for he would cling to his homelands as long as possible, and move south in waves rather than in slow steady streams, ejecting when possible the occupiers of the countries he invaded. It must also be remembered that occupants of inhospitable lands are generally more virile and warlike than their more favoured neighbours. Indeed throughout history civilised communities have regularly suffered from the irruptions of their more hardy and savage mountain bred or northern neighbours.

The fact that during the greater part of the earth's history the now frigid Arctic and Antarctic regions were semi-tropical in character, the Arctic Ocean being free from

ice and navigable, and that frigid conditions in the polar areas have been fleeting episodes, makes it practically certain that in the near future the present inhospitable condition of high latitudes will pass away, and that the great northern wastes of Europe, Asia and America, and perhaps the ice-bound Antarctic Continent, will become habitable by man, and what are now frozen seas will be highways of commerce for hundreds of millions of years.

Meteorologists cannot account for the climates of the globe being as they are by appealing merely to what takes place in the lower atmosphere. The same difficulty faces us when an attempt is made to account for past changes of climate. It is not as though there were signs of the earth's climate becoming colder with the lapse of time ; for one great glacial period occurred about one thousand million years ago when the habitable earth was comparatively young, and was followed by hundreds of millions of years during which the climate of high latitudes was so warm that there were no climatal zones at all comparable with those that exist now.

Instead of the upper atmosphere being the space of cold and quietude that it was once thought to be, we now know that in it are strong winds and great variations of temperature. Such being the case we can with reason consider that the activities of the upper air affect the lower atmosphere greatly, and an effort will be made to take into consideration these upper air conditions and show that they really do provide the missing forces required to cause the present distribution of climate, and also furnish good explanations as to why the past variations of climate have taken place.

CHAPTER II.

THE COMPOSITION OF THE ATMOSPHERE.

THE gaseous envelope of the earth is mainly composed of nitrogen and oxygen. It covers the oceans and continents, and deeply submerges the highest peaks of the earth's mountain ranges. In ancient times air was regarded as one of the four primordial elements, namely earth, air, fire and water, and when some odorous vapour was mixed with it, and it became scented, it was concluded that the admixture had in some unknown way modified its properties. The possible modifications of the atmosphere suggested by this theory were so very numerous that the problem of composition was regarded as insoluble. We now know that instead of being elemental in character in the sense the ancients supposed, pure air consists of a number of tasteless, colourless, odourless gases mixed together mechanically.

Although the general reader who wishes to understand meteorological phenomena need not study chemistry in any detail, a knowledge of the actual differences between the various substances which are mixed, or physically bound together, to form the atmosphere, is desirable ; for we shall be compelled to speak of solids, liquids and gases, of atoms, ions and molecules, and of elements and compounds. However, for our purpose the subject need not be treated in any great detail.

We instinctively desire to know what is the smallest portion of any body or structure. Thus in the case of a house we know that it is built of stone, bricks, mortar, wood, metal, etc. We are also aware that all these forms of matter can again be broken up into other substances which are often very different from each other, and also from the substance they produce when mixed. Mortar, for example, is formed of sand and lime, and brass from copper and zinc. Lead, on the other hand, is a pure substance or element ; it cannot be broken up by ordinary chemical processes into any other substances.

At one time it was thought that elements such as lead, gold, silver, oxygen, nitrogen, etc., were formed actually of indivisible atoms or particles, but we now know that atoms are complex structures the parts of which are so firmly

bound together that we are unable by any known means to break them up in quantities which would be of any use commercially, and that what little we can do in this respect is done only at very great cost.

For our purpose we need only consider the atoms of the elements and the molecules formed by their union the one with the other, the further subdivisions being a matter of no interest to the meteorologist at present. There are 92 known elements, and out of these units all the substances which occur in Nature are built up. However, even this statement is not quite the whole story, for there are other exceedingly minute entities which are not called elements, some of them being used to bind the atoms of the elements together, and others probably particles of which the elements are built up. So far four such bodies have been recognised—the neutron, the proton, the positron, and the electron. The question of the structure of the atom is now being carefully studied, and many new and important facts are being discovered.

In Meteorology we are concerned only with a few of the elements and the way some of them are combined to form the gases of the atmosphere. Fortunately the elements that go to form the gases of the atmosphere are few in number, and they are combined with each other in a very simple way.

The atmosphere is purest at great heights, over the oceans and mountain ranges, and over the snow- and ice-covered areas near the poles.

That the atmosphere consists of several gases having different chemical and physical properties was not recognised until the time of Boyle and Mayow, towards the end of the seventeenth century. Indeed it was not until 1783 that Cavendish demonstrated the fact that air is composed mainly of two gases which we now call nitrogen and oxygen.

In 1893 Lord Rayleigh discovered that the nitrogen prepared from ammonia is somewhat lighter than the nitrogen separated from the atmosphere, the deficiency in weight amounting to about 1 part in 200. Sir William Ramsay soon afterwards ascertained that the difference was due largely to the presence in air of a hitherto-unknown gas. This was called argon, and it subsequently proved to be one of a group of curiously inert elements. With the exception of carbon dioxide, which is a gas formed by the chemical union of one atom of carbon with two atoms of oxygen, and water vapour, all the principal constituents of the air are themselves elements mixed together mechanically.

As we have seen, soon after Lord Rayleigh had discovered that atmospheric nitrogen was abnormally heavy, Sir William Ramsay succeeded in isolating the inert atmospheric gases—argon, neon, helium, etc. At this time no idea was entertained that any of these gases was likely to be of any use.

It is well known that when an electric current is passed through a partially exhausted glass tube the rarefied gas becomes luminous, and the colour of the radiated light depends upon the nature of the gas. In the case of neon, so strong and brilliant is the red light given off, that it can be used for all kinds of illuminated signs, and it is claimed that the red neon tubule is visible by night and in fog from a much greater distance than any other light. Other colours and shades can be obtained. Thus by adding metallic mercury to the neon gas blue is given, and by filtering the blue through yellow uranium glass a green is achieved. In the ordinary way the filtering of the blue would lower the efficiency of the green light ; but by using uranium glass a strong additional green fluorescence is obtained through the action of the ultra-violet ray component of the mercury radiation. By using argon and helium white or gold is obtained. In all these cases different shades of colour can be produced by using different coloured glass. Much research and experiment have combined in bringing the neon tube to its present state of perfection.

Table I gives the constituents (with the exception of water vapour) of the atmosphere in volume percentages, with sufficient accuracy for our purpose.

TABLE I.

Gases of the Atmosphere.

Gas.	Percentage in Dry Air.	Atomic Weight.
Nitrogen	78·04	14·0
Oxygen	20·99	16·0
Argon	0·937	39·9
Carbon dioxide . .	0·03	...
Hydrogen	0·0001	1·0
Neon	0·0012	20·2
Krypton	0·000005	82·9
Helium	0·0004	4·0
Xenon	0·0000006	130·2
Ozone	0·00014	...

It will be noticed that in this table the volumes are given as percentages of dry air. Air containing the substances named is considered to be pure if they are present in about the quantities shown.

At low levels in many areas several other substances, both solid, liquid and gaseous are found to be present. Nitric acid in small quantities is generally present. Oxides of nitrogen are produced along the path of lightning discharges, and these combine with water to produce both nitric and nitrous acids. The combustion of coal in large towns, and the gases given off in volcanic regions, result in the presence of sulphurous acid in the air. Lightning also probably produces some ammonia, and in the presence of water vapour, chemical action often results in the production of substances which are valuable fertilisers and enrich the soil.

It must not be supposed that the relative volumes of the gases present in the atmosphere are always exactly as given by the figures in the table. However, in spite of the fact that the atmosphere is a mechanical mixture of many gases, its composition even near the earth's surface, and particularly at very great heights, does remain remarkably constant. This is due to the mixing effect of eddy currents and to diffusion, and although some air movements are local in character, many winds travel thousands of miles, and the air rises or falls over very large areas. At one time it was supposed that the upper atmosphere was so free from disturbances that its constituent gases separated out to some extent in the order of their densities under the action of gravity. This is now considered untenable in view of the movements we know to be taking place at high levels.

The oxygen, nitrogen and hydrogen are in the free state, each consisting of molecules built up of two atoms. The inert gases argon, neon, xenon, krypton and helium, are also in the free state, but are present as uncombined atoms. In carbon dioxide the oxygen is not free, being chemically combined with carbon to form molecules consisting of one atom of carbon and two of oxygen (CO_2).

The rare monatomic gases argon, etc., do not play any conspicuous rôle in the activities of the atmosphere. Indeed they are less active than nitrogen. Helium is given off with the gases escaping from some deep wells and springs. In Colorado it forms about eight per cent. of the gases given off from the Wingate sand at a depth of about 950 feet. As it is only twice the weight of hydrogen, and non-

inflammable, it is used for the inflation of airships, the annual production being measured in millions of cubic feet.

Nitrogen compounds, formed from atmospheric nitrogen in the roots of certain plants, are valuable fertilisers of the soil. Carbon dioxide, commonly known as carbonic acid gas, also plays an active part in the growth of vegetation, the carbon being separated from the oxygen, with which it is combined, by the agency of certain of the sun's rays acting mainly in the leaves of plants. The carbon combines with numerous constituents of the soil brought up from the roots, and the compounds so formed build up the tissues and necessary juices required by the plant. Carbon dioxide, ozone, oxygen and water vapour also play a part in the warming of the atmosphere, by intercepting some of the sun's heat rays.

Ozone, the molecule of which consists of three combined atoms of oxygen, is present in minute amounts in country places, but is absent in towns and thickly populated areas. However, it is formed, probably by ultra-violet light, mainly at a height of 20 kilometres in the upper atmosphere, where its presence indicates that the sun emits radiations which are there intercepted and heat the air.

Oxygen is of tremendous importance, as animal life would be impossible without it. On this account it shares with carbonic acid gas and nitrogen the distinction of being one of the three most important constituents of the atmosphere. However, it is inadvisable to single out one or more of the constituents of air as being of supreme importance, for the processes which go on in living matter depend for their activities upon the presence of many other elements and compounds, such as are taken up from the soil by the roots of living plants in large or even very minute proportions. Oxygen also exists dissolved in water, as does carbonic acid gas, and as a consequence creatures such as fish can breathe freely in that liquid. As a climatic agent of change in the atmosphere it is, however, of less importance than either water vapour or carbonic acid gas.

Table I does not take cognizance of water vapour. The gases in this table are those, except in the case of ozone, which remain remarkably constant in their comparative volumes from year to year and from place to place. It was pointed out long ago by Dalton that the ultimate pressure of any vapour in contact with its liquid form depends only upon the temperature. Experiment proves that the maximum quantity of aqueous vapour which can exist in a given space in contact with water at a given

constant temperature is the same whether the space be otherwise vacuous, or filled with air at atmospheric pressure or with air under several atmospheres of pressure. Perfectly dry air brought into contact with water in a closed vessel will, of course, have its pressure raised by the evaporation of the water. The higher the temperature the greater the pressure of the vapour under such conditions. When air is present the only effect it has is to check the rapidity of evaporation, and a dry wind blowing over a water surface will produce more rapid evaporation than if the air were moist. Gentle winds move steadily in a direct manner, but in a moderate breeze there are eddies in the air current which promote rapid mixing. The vapour given off by water, when the air is steady, slowly passes into it by diffusion, the amount of vapour near the water surface being much greater than at some distance away. When the air flow is rapid and turbulent, however, thin layers containing much water vapour are stripped off, and fresh dry air comes in contact with the water surface. (As an analogy sugar dropped into tea will take a long time to dissolve if the liquid be not agitated with a spoon). The more still the air the more slowly will evaporation take place, but the quantity of vapour ultimately collected in a given space depends upon the temperature only, and will be practically the same whatever the pressure of the air present.

Regnault found that at a temperature of 59° F. one cubic foot of space is capable of containing 5·58 grains of water vapour. This will be dealt with more fully later.

Although the compound water (H_2O) exists in the atmosphere in both the solid, liquid and vaporous conditions, much the greater portion of it takes the form of invisible vapour. In the liquid state it is seen as haze, fog, mist or cloud, whilst in the solid condition it is generally snow, hail or small ice crystals. Condensed on the earth's surface it is much more abundant, for in its liquid state it forms the oceans, seas, lakes and rivers ; whilst as a solid it is present as snow fields and glaciers. An *ice crystal*, although possessing peculiar physical properties, can more correctly be described as being a solid than a liquid. However, when we come to deal with large masses of ice such as glaciers, which consist of immense numbers of crystal grains frozen together, we find that it runs down valleys and spreads over water surfaces after the manner of pitch or shoemaker's wax, and thus in mass behaves as a very sluggish (viscous) liquid.

We are here mainly interested in water when it exists

as a vapour mixed with air. Below the freezing point even ice evaporates and gives off vapour, but the vapour pressure is then very small on account of the low temperature. Table II gives the pressure of aqueous vapour in millibars at several temperatures.

TABLE II.

Pressures of Aqueous Vapour.

Temp., ° C.	Pressure, mbs.	Temp., ° C.	Pressure, mbs.	Temp., ° C.	Pressure, mbs.
−30°	0·53	15°	16·93	60°	198·3
−25°	0·80	20°	23·19	65°	248·1
−20°	1·20	25°	31·32	70°	310·7
−15°	1·86	30°	41·99	75°	383·4
−10°	2·80	35°	55·72	80°	472·6
− 5°	4·13	40°	73·18	85°	577·1
0°	6·13	45°	95·17	90°	700·3
5°	8·66	50°	122·6	95°	844·8
10°	12·26	55°	156·6	100°	1013

It will be noticed that the pressures are given in millibars instead of inches of mercury. It is very easy to remember that one atmosphere is 1013 millibars. Any pressure above this in our latitude may be said to be high and any pressure below to be low. The millibar is a very convenient unit; for 1013 we can merely write 13 and for 990, −10, the 1000 being added when the calculations are finished. There are those who are opposed to all such changes as the adoption of the millibar as the unit of pressure. To the scientific man such simplifications are necessary. The millibar, for example, is simple to use and bears a close relation to other generally accepted scientific units. In the interests of progress such changes must be made. Chinese writing, for example, requires the use of about two thousand signs, and very many years of study are required to enable a man to express his thoughts in this form of writing. We pride ourselves that we have adopted a phonetic system and have cut down the number of signs required to twenty-six letters and ten figures. But the phoneticism of our writing is so imperfect that there are few people who have reached manhood who can write and spell in a manner which is considered correct, and the written word is not used as a means of teaching pronunciation.

When will imperfect phoneticism cease to trouble us, and the young be given a chance of learning quickly to write and speak their language? We are tempted to write in this strain on account of the opposition of many literary persons to such a substitution as millibars for inches or centimetres of mercury.

The table shows that at low temperatures the pressure of aqueous vapour is very small. When the pressure is 1000 millibars, and the temperature $-30°$ C., the air being saturated with water vapour, the actual pressure due to the air is 999·47 mbs. In winter the average temperature at a height of about 7·5 kilometres is $-30°$ C. and the aqueous vapour pressure 0·5 mb. At the earth's surface the temperature is then about 0° C. and the vapour pressure 6·1 mbs., twelve times as great.

In the upper regions of the atmosphere, owing to the low temperatures which prevail at the top of the troposphere (or lower atmosphere), water vapour must exist in negligibly small quantities. It is at the earth's surface near the equator that the atmosphere contains most water vapour. In high latitudes the amount is small.

Our rains are the result of chilling by radiation or the formation of cloud as the air containing water vapour rises and cools. When damp winds blow up slopes, and over high ridges and mountain masses, rain clouds are formed. In depressions rain results rather from warm winds over-riding other winds, or from the bunching together and consequent rise of the air. At the centres of depressions we often have clear skies. We thus conclude that there seldom is a pronounced and continuous rise of the air in the centre of depressions. The vertically rising air is generally on one or two sides of the depression, and the rain may be the result of chilling owing to change of latitude as well as uprise. At a later stage this point will be more fully considered.

In addition to its gaseous constituents the atmosphere contains large numbers of dust particles in suspension. They are so small, and settle so slowly, that very gentle upward currents lift them to great heights. On Ben Nevis experiment revealed the presence of 40 particles per cubic centimetre. The following figures give the number of dust particles per c.c. under various conditions:—

In the open, raining	32,000
In the open, fair	130,000
Room	1,860,000
Room near ceiling	5,420,000
Bunsen flame	30,000,000

It has been calculated that the smoke particles obtained from one cigar with every puff of smoke reach the large sum of four thousand millions.

Over very dry areas the ground surfaces are broken up by alternate heating and cooling, the solid rocks being reduced to fine particles, which are picked up by the wind and often carried many hundreds of miles before they can settle or are carried down by rain. When the wind is strong heavier particles are carried along near the ground, erode pebbles into peculiar forms called "dreikanter," and undercut cliffs, or indeed anything that projects above the surface. In this way the heavy particles are themselves ground to fine dust, and this dust rises to great heights, eventually settling to the ground in calm areas, and forming deposits called "loess" hundreds or even thousands of feet thick.

Immense quantities of solid material are thus removed from large areas, producing deep depressions in the earth's surface which often descend below sea-level.

Dust is often picked up by air whirls, which are common in desiccated districts, and is distributed by winds blowing over such areas.

In the case of great volcanic eruptions, such as those of Krakatoa in 1883, Monte Pele and Sante Maria in 1902, and Katmai in 1912, dust was thrown into the upper atmosphere to great heights, and gave rise to a sort of reddish-brown corona, visible under favourable conditions, around the sun. From the optical phenomena produced, the diameter of these small particles appeared to vary but little from 1·85 microns. The rate of fall of such particles is very slow. It has been estimated that it would take about one year for such particles to fall through the lower 24 kilometres of the upper atmosphere (stratosphere). As much of the dust may have consisted of thin-walled bubbles it probably took two-and-a-half or three years for much of it to fall through the stratosphere.

Particles of dust in the upper atmosphere no doubt cut off some portion of the sun's rays and prevent it from reaching the earth, thus lowering the temperature of the troposphere and raising that of the stratosphere. It is very doubtful, however, if at any time during the earth's history volcanic action has been so intensive as to keep the upper atmosphere continuously charged with dust to an extent sufficient to appreciably alter the climate. Such eruptions as have occurred in historical times have evidently had very little effect.

Another form of dust, which produces striking optical

effects such as halos, results from the formation of ice crystals or snow in the atmosphere.

The presence of dust in the higher atmosphere is interesting rather for the information it gives concerning the upper air currents, than of itself, as an important component of the atmosphere. However, as already indicated, it has been suggested that much dust in the atmosphere would have climatic effects.

Great volcanic eruptions, such as that of Krakatoa, throw dust particles to enormous heights, and they become widely distributed by air currents in the upper atmosphere. In the case of Krakatoa by thin filtering effects upon sunlight beautiful sunsets were produced.

The passage of sunlight through the air has some remarkable electrical effects upon the molecules of the gases forming the atmosphere. What are called "ions" are produced. All atoms and molecules contain electrons (negative electrical charges), and when these electrons are torn from the atoms, the atoms become positively electrified and the electrons move about independently as negative particles. The gas is then said to be "ionised." The number of ions of each kind (positive and negative) produced per second in each cubic centimetre of air is about twenty, and when ions of opposite sign approach each other closely they unite. Each ion when free draws to itself molecules of water vapour, if these are present, and forms complexes capable of acting like dust in the formation of cloud. Indeed, the particles formed by the condensation of water on ions are visible to the naked eye. Their presence produces many interesting meteorological phenomena ; but, as yet, they have not been shown to have any very important bearing upon the principles which give rise to climate. On this account they need not be referred to further here.

CHAPTER III.

INSOLATION AND SCREEN TEMPERATURES.

THERE is no doubt but that practically all the heat the earth receives comes from the sun in one way or another; but the distribution of the heat, thus received, throughout the atmosphere, is such that it is difficult to see how it can be wholly received in the form of light and heat waves. On this account the effects of insolation, *i.e.* the exposure of the earth to the sun's rays, must include the heating effects of material particles or corpuscles which the sun radiates into space, and which reach the earth's atmosphere.

As a result of the irregular heating of the atmosphere due to the alternation of day and night, the inclination of the earth's axis to the plane of the ecliptic, and other circumstances, the pressure of the air on the earth's surface, due to its varying temperature and density, varies greatly, from place to place, and often in a singular manner. For example, pressures in high latitudes are low, just where we should expect the air to be cold and heavy. If the material radiations of the sun do affect the temperature of the earth's atmosphere, it can only be at considerable heights, for they are unable to penetrate air for any great distance.

Although the result of the heating by corpuscles of the upper atmosphere is apparently important, it is the effect of heat and light rays that will mainly be considered in this chapter.

What are known as heat and light rays can pass through the cold of space without heating it at all. In space, at a distance from suns and planets, matter is almost absent, there probably being not much more than one atom or molecule to each cubic inch. Such waves as those of light and heat possess energy, and when they strike dense masses of matter what happens depends upon the kind of matter encountered; the waves may be almost entirely reflected, transmitted or absorbed. Rocksalt is almost perfectly transparent to heat waves. Glass is not, and such waves as are not transmitted by it result in heating effect.

The scorching rays of the sun, for example, have passed through about 93,000,000 miles of space, where it is so cold

that gaseous matter in the shade would first liquefy and then freeze solid. The atmosphere, solid earth and oceans, arrest these radiations, and transform them into heat, with the result that the surface of our globe is rendered habitable.

The energy we receive from the sun is again radiated into space ; for the temperature at each point on the earth will rise until as much heat is radiated into space as is received from the sun. The heating, however, is irregular and the temperature therefore varies. For example, during daylight the earth is receiving heat and light rays from the sun and its temperature rises ; but during the night it receives no heat rays of this description, and the temperature falls until the rising sun heats the earth again.

We are, in this chapter, dealing for the most part with the temperature of the air about five feet above the ground, at sea-level. To some extent air temperatures at other levels will, however, have to be considered, for in most cases corrections have to be made in the observed figures on account of the varying heights of observing stations above the sea.

All the energy which reaches the earth and raises its temperature so considerably is radiated in one form or another by the sun. Some of the radiations have exceedingly short wave-lengths. Wireless wave-lengths are reckoned in metres, heat wave-lengths in hundred-millionths of a centimetre, whilst X-rays are enormously shorter. We know also that the sun throws out corpuscles, which may strike the upper atmosphere and heat it. There are thus three types of energy to consider :—

(1) Cosmic radiations from space.
(2) Heat and light waves from the sun.
(3) Corpuscles from the sun.

The cosmic rays are very penetrating, and some of them pass through the atmosphere to the land and ocean surfaces, which they penetrate to depths measured in tens of yards. Heat and light rays are stopped to the extent of 25 or 30 per cent. by a clear atmosphere, but owing to the presence of water vapour, cloud, etc. from time to time, this proportion is often greatly exceeded. Light and heat waves do not penetrate the land or water surfaces very deeply. The earth is a very bad transmitter of heat rays, for the solar radiation falling upon it warms only a thin layer each day, but this heat does pass into the crust by conduction. In the tropics, where there is little variation in the daily air temperature, the ground remains at a constant temperature

below depths varying from three to twenty feet. In middle latitudes, where the daily and seasonal temperature range is greater, the "invariable layer" is reached at a depth of about 60 feet. In the oceans, where the surface waters are drifted by the winds into partially closed areas, and piled up there, the sea is warmed by convection currents to depths of between 600 and 1000 fathoms. At great depths the oceans are very cold. This is brought about by the sinking of cold Arctic and Antarctic water largely resulting from the melting of ice. Enclosed seas, such as the Mediterranean, are much warmer at considerable depths, for they are cut off by shallow ridges from the cold water supplies. Little is known concerning the electrons and electrified material radiations of the sun. That the earth receives heat in this way is clear, but the proofs that this is so are indirect ones. The matter will be discussed later.

It has already been stated that the amount of heat or energy the earth receives from the sun is unequally distributed, largely owing to the low elevation of the sun in high latitudes, and that this unequal distribution is the cause of our seasons. However, it is clear that as regards climate much may also depend upon the intensity and constancy of strength of the sun's rays. When we consider the remarkable changes of weather that take place, not only from day to day, but from year to year, we naturally wonder if this may not be due in some measure to changes in the quantity of energy received from the sun. The matter really is one that calls for serious consideration. We know little concerning the variability of the cosmic rays, and have no reason to believe that either directly or indirectly they can have any material effect upon the earth's temperature. However as regards light and heat waves from the sun, the work of American observers has taught us a great deal concerning their intensity and variability, and this matter may well receive some attention here.

We know that the sun is continually radiating energy into space, only a very small portion being intercepted by the earth. The quantity of heat energy, in calories, which would fall in one minute on an area of one square centimetre placed to face the sun, is called the *solar constant.* It is measured on some very elevated spot, so as to avoid as much as possible the absorbing effect of certain constituents of the atmosphere. Corrections for absorption occurring at higher levels than the observer are then made by considering the variations found as the sun increases and decreases in

altitude during the day. Langley devised instruments of great accuracy for carrying out these corrections.

The value of the solar constant has also been measured by Abbot and Fowle, who find for the mean value 1·94 calories. Daily measurements of the value are made at Montezuma, Chili. During the period 1924–1930 these have shown among other changes a rough five-day period, readings as high as 1·965 and as low as 1·905 being recorded. The accuracy of these observations it is considered has been confirmed by simultaneous observations made at two other stations. Some daily values of the "solar constant" are given in Table XVII.

There are two scales of temperature in common use. Fahrenheit in 1714 introduced his thermometer. He made use of mercury as the liquid to be expanded by heat in a glass tube, and the two points used for graduating the instrument were the melting-point of ice and boiling-point of water, 32° being adopted for the melting-point and 212° for the boiling-point. The selection of these two values for graduating purposes was unfortunate. However, about 28 years later Celsius made the boiling-point of water 100° and the melting-point of ice 0°. The centigrade thermometer of Celsius is the one generally used for scientific purposes, but many adhere to the arbitrary and awkward scale of Fahrenheit. Although the centigrade scale is undoubtedly the better, both scales will be used here, some charts and tables being in one scale and some in the other.

The fact that the earth is habitable by animals and plants may be regarded as being an extraordinary accident, so many circumstances having combined to make the earth as it is ; and as far as we know it is the only world of its kind. However, there are so many bodies in space about which we know very little, that the possibility of the existence of other worlds somewhat like our own as regards temperature and atmosphere is not improbable.

For meteorological purposes the two important globes are the earth and the sun. The time the earth takes to circle around the sun once is called a "year." Such is the size and heat of the sun that it is able to maintain the earth in a habitable condition, although it is moving through intensely cold space at a distance of 93,000,000 miles. Owing to its comparatively rapid rate of rotation, and the fact that its surface is covered by an atmosphere and oceans which retain and distribute the heat received from the sun, the earth's surface temperature is prevented from reaching extremes either of cold or heat, except in high latitudes. The

blanketing effect of clouds, fog and mist also helps to prevent rapid fluctuations of temperature near the earth's surface.

When the air is very dry, as is the case in desert areas near the tropics, the days are uncomfortably hot and the nights very cold. If the air were quite pure and consisted only of the gases named in Table I, it would be largely transparent to heat rays, and the greater part of the rays would reach land and water surfaces. The atmosphere, however, contains water vapour, carbonic acid gas, ozone, cloud, mist, fog and dust particles, and sometimes almost the whole of the sun's radiation is cut off by them and does not reach the solid and liquid earth. The actual proportion of the sun's heat intercepted before it reaches the earth varies greatly from time to time, and from place to place, the lower atmosphere especially acting very irregularly in this respect. On a plateau 3,000 metres high, the sun's rays have lost about 30 per cent. of their heating power, even when the air is bright and clear, and it has been estimated that on an average only about 24 per cent. of the heat radiations of the sun reach the ground and water surfaces.

On the earth, for many reasons, the variations of temperature are very considerable, and it is these differences we are now about to consider. When we say that the variations are very considerable, we are considering temperatures from the point of view of their effect upon life; for in both the hottest and the coldest localities life is almost impossible. When, however, we consider the range of temperature as compared with the actual zero of cold ($-273°$ C.), the change in the earth's surface temperature is only about 15 per cent. above and below the mean.

If the light and heat received from the sun fell upon a globe whose axis of rotation was always normal (vertical) to the plane of the globe's rotation (the ecliptic), the day and night on that globe would be of equal length throughout the year at all latitudes. Under such conditions there would be no seasons, for the sun would rise and set at the same points throughout the year, and its altitude at midday would always be the same.

We must not assume, however, that under such conditions similar variations of temperature would take place each day; for, as already stated, the solar constant is not invariable. However, the temperature changes due to variations in the solar constant are of too short a period to have much effect. The uncertainty arises from the fact that weather changes, other than seasonal ones, seem to be

much too marked to be due to any known variability of the heat and light rays of the sun. This point cannot be discussed here ; but it may be mentioned that it will be contended in another chapter that the great variability of the weather, both during winter and summer, may result from variations in the intensity of corpuscular radiation from the sun.

The inclination of the earth's axis to its orbit, as shown in Fig. 1, gives us our seasonal changes, especially in middle and high latitudes, and the fairly regular changes which we distinguish as summer and winter. We thus have warm summers in high latitudes where the air would otherwise be too cold for vegetation throughout the year. We must look upon the inclination of the earth's axis to the ecliptic as a phenomenon which makes it possible for us to live and grow crops in higher latitudes than otherwise would be the case.

The irregular distribution of land and water, and the inclination of the earth's axis to the ecliptic, are therefore largely responsible for our seasonal weather changes. However, in this chapter we are only considering the temperature conditions as we find them at the earth's surface.

The aim of the meteorologist for climatic purposes is to obtain the temperature of the air a few feet from the ground. This can only be done satisfactorily by taking care that the thermometer is not directly exposed to the sun's rays or the radiated heat from surrounding objects. One plan is to attach the instrument to a short chain or cord and swing it round and round through the air. When this is done readings should be taken as quickly as possible after the instrument comes to rest. The usual plan is to enclose the thermometer in a screen. Special shelters of this kind have double roofs with double-louvred sides to permit a free circulation of air through the screen. Such screens are placed with their bottoms 3½ feet above the ground, and the louvred doors made to face the north. With all these precautions, on a hot summer's day the temperatures obtained are apt to be a little low, and on a still cold night too high.

For the purpose of drawing charts showing lines of equal temperature (isotherms), allowances must be made for height above sea-level, and where there are hills and sheltered valleys, observations in exceptionally-placed positions should be avoided. For most scientific purposes the actual isotherms are too complicated. Indeed, owing

to the fact that the temperature decreases with height 800 times faster than it does with latitude, correct isothermal maps of England, for example, look very like contour maps showing elevations. The charts to be figured are mostly after Buchan, and an allowance is made on the assumption that the temperature falls 1° C. as we rise through every 150 metres, or 1° F. for every 270 feet. As a matter of fact changes of temperature with altitude show very considerable variation from day to day and year to year, but in making isothermal maps a uniform reduction allowance has generally been employed, and the errors reduced as far as possible by utilising observations taken at low levels.

To obtain the actual mean temperature of any place crossed by an isotherm on the maps shown, it is necessary

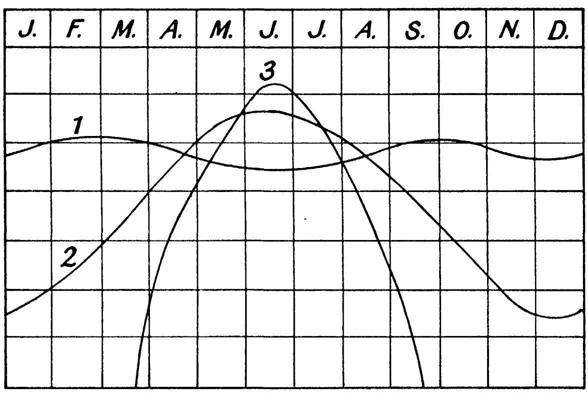


Fig. 8.—Insolation Curves at Various Latitudes.

only to subtract from the temperature given an amount obtained by dividing the height of the place in metres by 150, to get the mean centigrade temperature.

The actual amount of heat received at any particular latitude depends upon the length of the day and the height of the sun above the horizon from hour to hour. On Fig. 8 are plotted the comparative amounts of heat received at the earth's surface during the year due to these two considerations, (1) at the Equator, (2) at north latitude 45°, and (3) at the North Pole. As the sun crosses the equator twice during each year, and the lengths of lay and night there are always approximately twelve hours, there are two maxima and two minima of insolation, the latter occurring at the solstices when the sun is above the tropics of Cancer and Capricorn. In latitude 45° the sun is never overhead (in the zenith), but during the summer the days are so much longer than at the equator, and the nights so much

shorter, that the heat received during June is actually greater at that latitude than at the equator. At the North Pole the sun is above the horizon continuously for six months, and although it never rises very high ($23\frac{1}{2}°$), the heat received during June on the ground is greater there than at the equator for the same month. Indeed during May, June and July the pole vies with the equator in the heat it receives. However, during the long winter the loss of heat is so great, owing to surface radiation, that the sun is not able to get rid of the snow and ice formed during this season, although the air temperature in summer rises to 32° F. and the ice and snow are then continually exposed to the sun's rays.

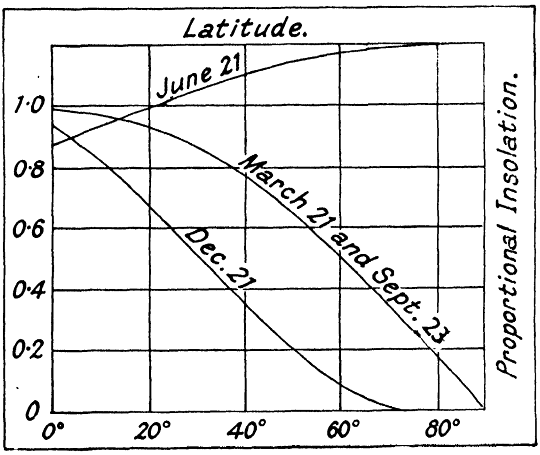


Fig. 9.—Insolation Curves for Solstices and Equinoxes.

At latitudes higher than $23\frac{1}{2}°$ there is only one maximum and one minimum of insolation during the year, and this accounts for there being one winter and one summer in temperate regions for each revolution of the earth round the sun. It will be noticed that the insolation curve (Fig. 8) for the equator is not quite symmetrical. This is due to the eccentricity of the earth's orbit, the sun being more distant from the earth during June than it is in December.

Although there is in latitude 45° during May, June and July an excess of heat received over that received in equatorial regions, there is a marked deficiency during the rest of the year. At the North Pole, for example, although the summer insolation is so great, the heat received for the whole year amounts only to 41 per cent. of that received at the equator.

Fig. 9 illustrates how the great length of the day at the

poles on June 21 more than compensates for the decreasing angle at which the solar rays strike the earth. The diagram gives the proportional amount of insolation in twenty-four hours at different latitudes at different times of the year. The heat received on March 21 and September 23 is shown as being the same ; but this is not quite correct, owing to the eccentricity of the earth's orbit.

The total comparative annual amounts of insolation for every 5° of latitude have been calculated by Hann, and his results are given in Fig. 10, curve *A* without atmosphere and curve *B* with atmosphere. The unit adopted is the

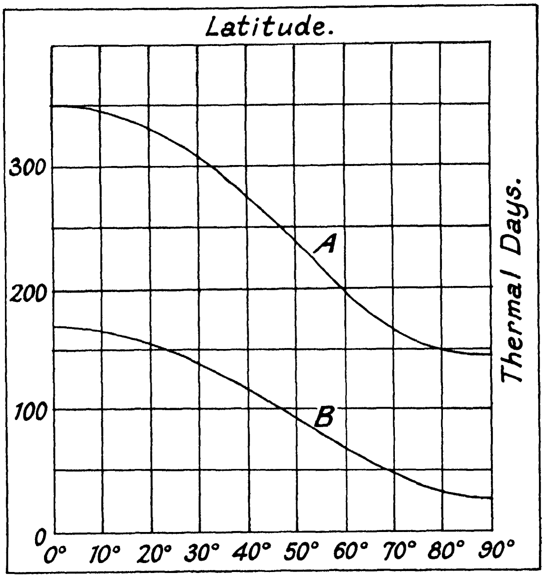


Fig. 10.—Total Annual Comparative Insolation for Different Latitudes.

amount of heat received at the equator in one day at the time of the equinox.

So far, with regard to these data, except as regards Fig. 10, the atmosphere has been regarded as transparent, the solar heat penetrating it and reaching the land, water, snow or ice. However, this is far from being the case, as Fig. 10 shows, for the atmosphere is not transparent but intercepts on an average about 76 per cent. of the incident solar heat and light energy, leaving only 24 per cent. to reach the earth's surface. When the sun is obscured by clouds, practically the whole energy is absorbed, and even when the sky is clear and cloudless only about 50 per cent. of the sun's rays reach the earth. In high latitudes the interception

of the solar heat is still more considerable, the rays of the sun, owing to its low altitude, having to pass through a thicker layer of air. The diagram Fig. 11 has been drawn on the assumption that 78 per cent. of the radiated heat and light energy reaches the earth when the sun is in the zenith. Here the curve *A* gives the proportional amount of this energy that reaches the earth at various latitudes when the energy strikes a surface placed normal to the rays. On the other hand when the energy strikes the horizontal surface of the earth the insolation at each latitude is as shown by curve *B*.

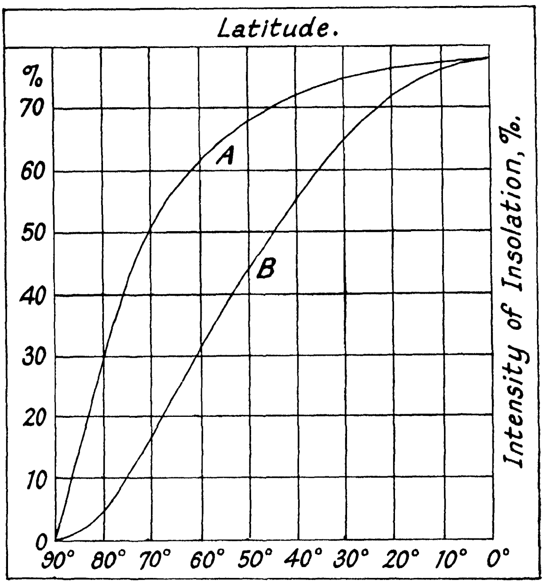
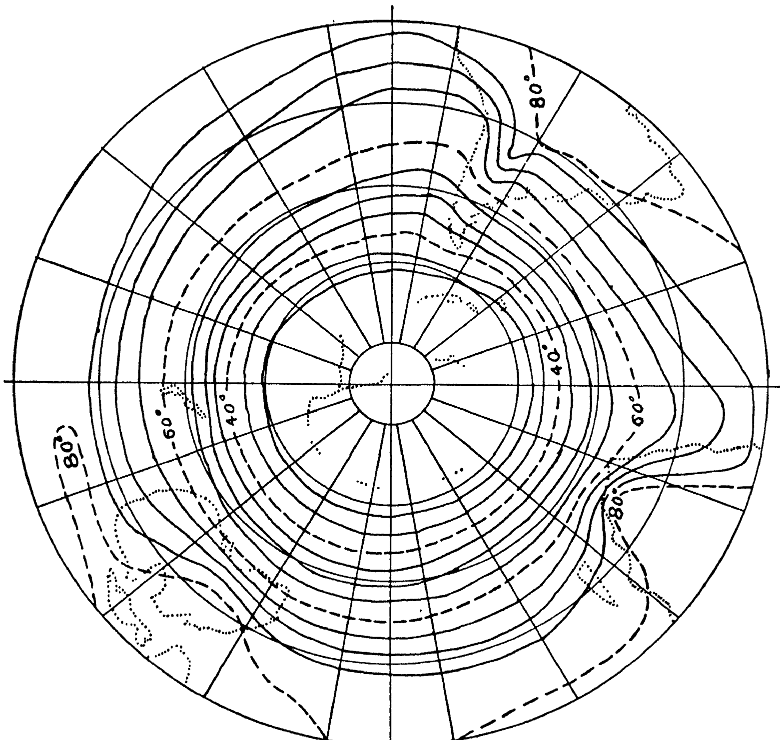


Fig. 11.—Insolation Curves for Surface Normal to Sun's Rays and for Horizontal Surface of Earth.

The transparency of the atmosphere varies irregularly with the hour of the day and with the season of the year, and also with the amount of water vapour present. Clouds also affect its transparency, as also do oxygen, ozone, carbonic acid gas, dirt, etc. The coefficient of absorption is least at moderately high altitudes and over more or less rainless areas. Absorption has, in consequence, to be expressed in approximate percentages rather than in actual units.

Except for some special purposes the question as to whether solar heat is absorbed by the lower atmosphere or the ground does not greatly matter. This will be better understood when we come to deal with the vertical



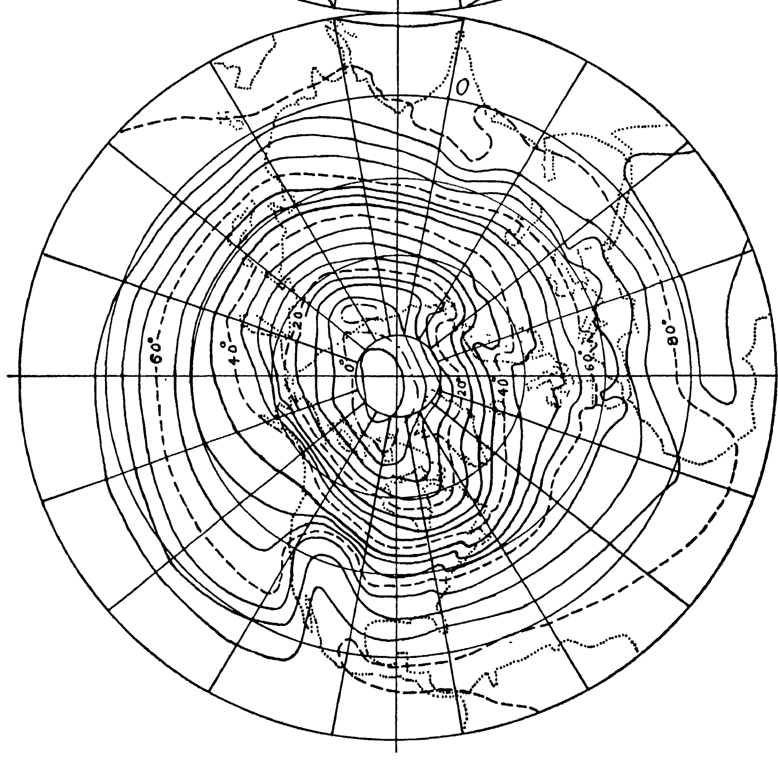


Fig. 12.—Mean Annual Isotherms of Northern Hemisphere. Fig. 13.—Mean Annual Isotherms of Southern Hemisphere.

distribution of temperature in the air: as long as the disparity between the heat arrested by the air and ground is not great at high levels, the vertical temperature gradient in the air, and therefore the temperature of the air over the ground, is not greatly affected. It is to the winds and ocean currents that we must ascribe the fact that the temperatures met with in many localities are not such as we should expect from the coefficient of transparency of the atmosphere at the places. This will become more and more evident as we come to deal with the winds and barometric pressures.

We are now in a position to consider the distribution of surface temperature throughout the globe.

Figs. 12 and 13 show the mean annual temperatures of the Northern and Southern Hemispheres. The lines of equal temperature, called *isotherms*, are much more regular in the Southern than in the Northern Hemisphere, and run round the Antarctic Continent with very little distortion over the oceans. In the Northern Hemisphere the temperatures are lowest over North America and Asia. East and south of Greenland the isotherms pass in a north-easterly direction, indicating the high temperature of the North Atlantic and adjacent portions of the Arctic Ocean. This is due to the prevalent south-westerly winds. A very strong current of very warm water passes through the Straits of Florida and flows north-east, some little distance from the shores of North America. It is called the Gulf Stream. In addition to this, warm water from the western portion of the North Atlantic also drifts to the north-east, and the prevailing south-westerly winds carry it and the waters of the Gulf Stream to the shores of Europe, and up into the Arctic Ocean. Indeed it will be seen that the ocean currents and drifts closely agree with the prevalent winds, the winds being the motive power and the water the great heat reservoirs.

Apart from the irregularities introduced by the irregular distribution of the land and sea and the direction of the winds and ocean currents, the temperatures as a whole are roughly such as we should expect from the variation of the effective insolation as we pass from the equator to the poles.

In the Southern Hemisphere the area of land as compared with that of water decreases greatly as the Antarctic Continent is approached. Here the isotherms run much more regularly than they do in the Northern Hemisphere.

Figs. 14 and 15 illustrate the temperature differences in the Northern Hemisphere as between January and July. During the winter in Asia the air temperature falls to -50° F., whilst in the summer the shores of the Arctic

Sea are at or above 40° F., a range of 90° F. In the Northern Hemisphere, between latitudes 20° and 40° during winter, the isotherms follow the lines of latitude with some show of agreement. During summer, however, this agreement is not so close and the elevated continental areas are comparatively hot, even on the high Asiatic plateaux. We must not forget that the temperatures are reduced to sea-level.

In the Southern Hemisphere, as shown by Figs. 16 and 17, the land areas are naturally hotter in the summer than in the winter, as also are the seas near the Antarctic continent.

There being a close connection between the temperature of the air and the water upon which it rests, the part played by the oceans in retaining and distributing heat deserves notice.

It will be seen that if there were no atmosphere, and no water-covered areas, to store the unreflected portion of the sun's heat, insolation would raise that portion of the earth's surface exposed to it to a high temperature, whilst that portion which was in shadow would be greatly chilled by radiating its heat into space. Under such conditions, there would be a very great difference between day and night temperatures, and, within certain limits, this would be the more pronounced the longer the day as compared with the night. It has been calculated that if there were no water or atmosphere, the mean temperature of the day in low latitudes would be 370° F., whilst the mean temperature of night would be −123° F., a range of 493°! At the poles the average temperature would be much below that at the equator owing to the fact that the sun does not at any time rise high in the heavens, and the rays thus strike the earth obliquely. The atmosphere and the oceans, however, act as great heat reservoirs and by their movements largely prevent very violent fluctuations of temperature.

There being, as stated, an intimate connection between the temperature of the air and that of the water surfaces it is in contact with, the ocean temperature requires consideration. In both cases there is a falling off of the temperature as we pass from low to high latitudes. At moderate distances from the land, in the neighbourhood of the equator, there is a mean surface temperature of from 82° to 84° F. In these low latitudes the diurnal changes often scarcely exceed one degree, whilst the annual changes are not greater than 5° F.

When one remembers that one square metre of the ocean's surface one metre deep holds as much heat as one

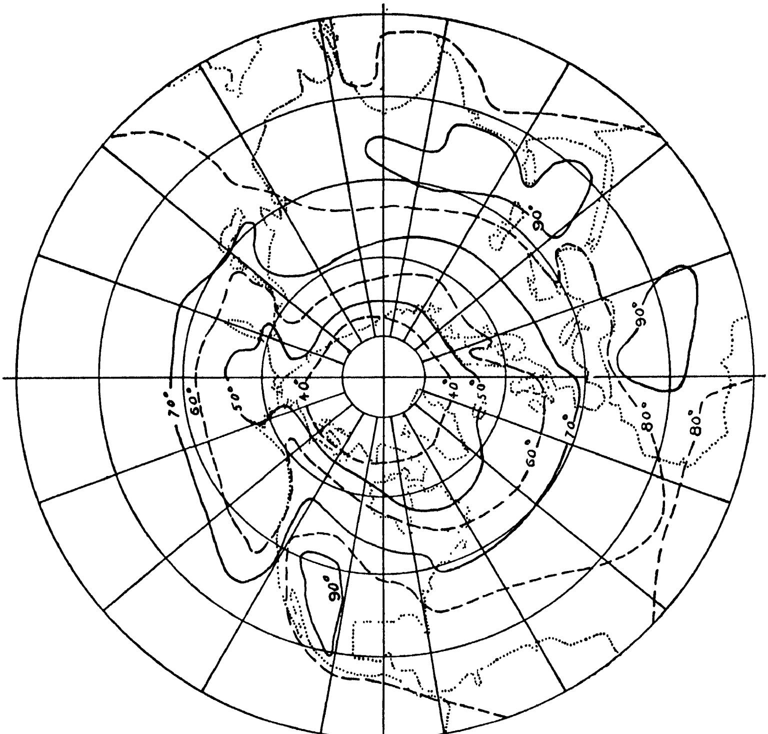


Fig. 15.—Mean July Isotherms of Northern Hemisphere.

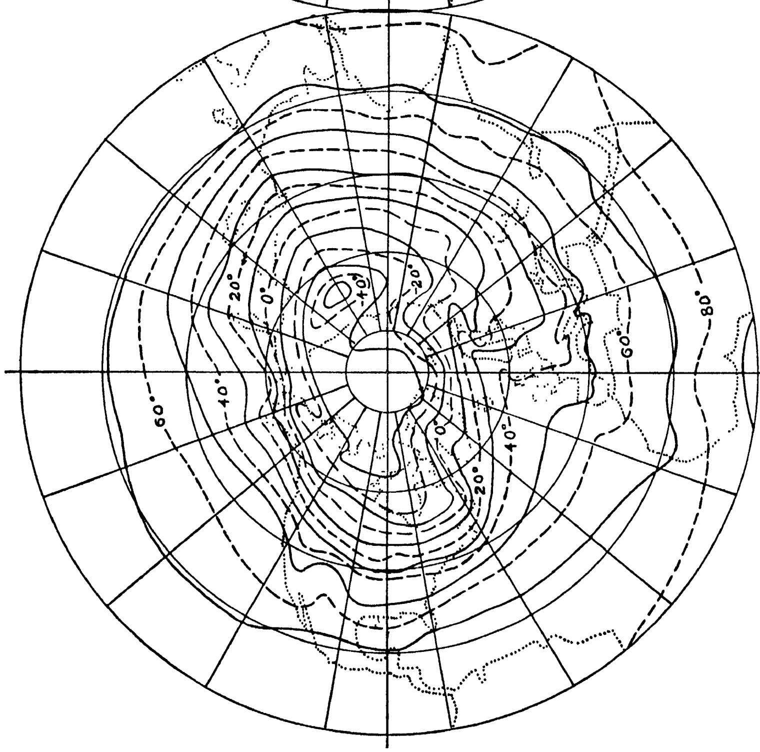
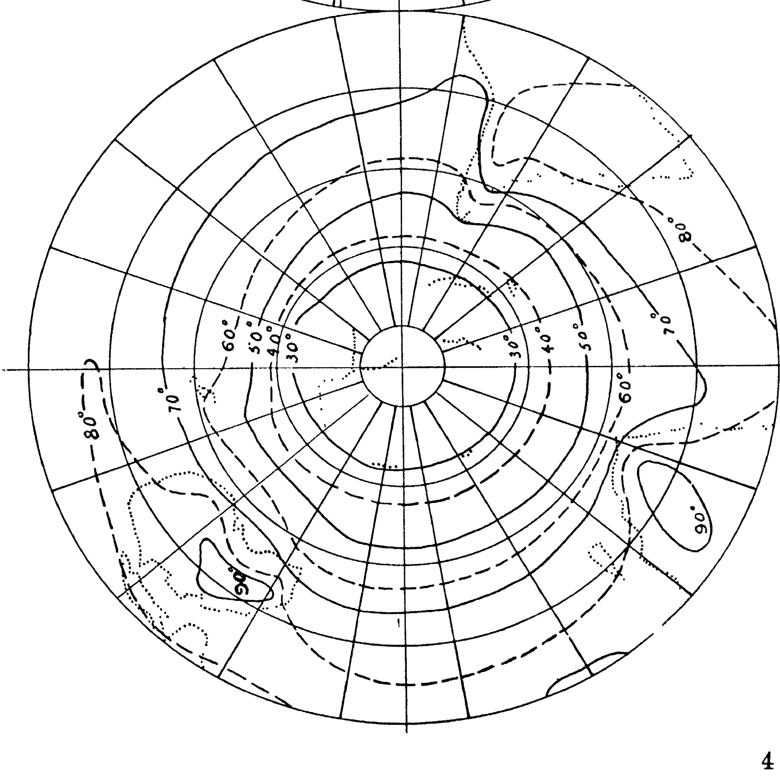


Fig. 14.—Mean January Isotherms of Northern Hemisphere.



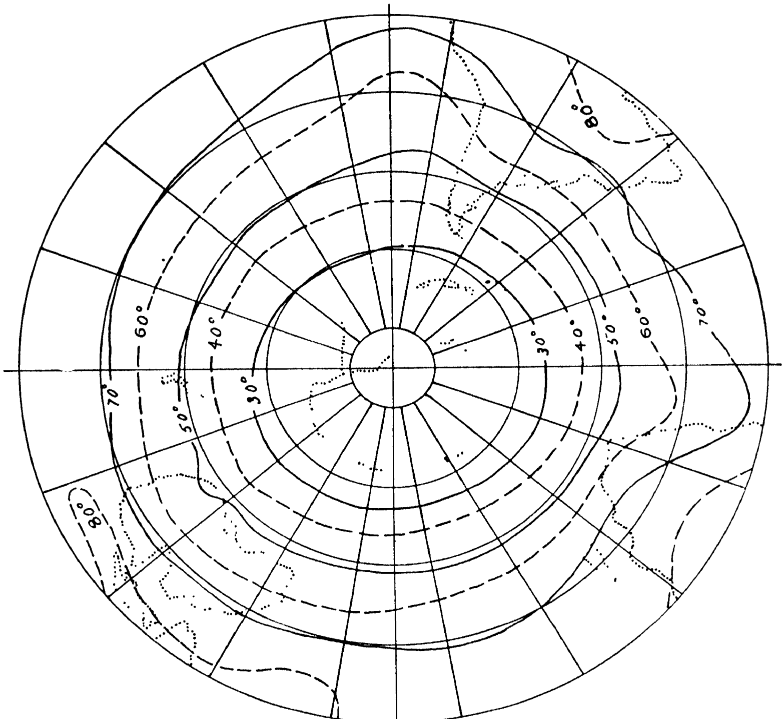


Fig. 16.—Mean January Isotherms of Southern Hemisphere. Fig. 17.—Mean July Isotherms of Southern Hemisphere.

square metre of the atmosphere three thousand metres thick, it becomes clear what great reservoirs of heat the oceans are.

Fig. 18 is a section of the upper 1000 fathoms of the North and South Atlantic Oceans, showing the variation of temperature with depth, along longitude 30° W. Both at the northern and southern ends of the section, between latitudes 70° N. and 60° S., the land reaches the sea-level on the coasts of Greenland and the Antarctic continent, and the pack ice is encountered. It is impossible to show the floor of the ocean, for the section only goes down to 1000 fathoms, whereas the ocean floor is in places 8000 fathoms below sea-level. Below 1000 fathoms the temperature falls to 28° F., the freezing-point of salt water. Indeed the great

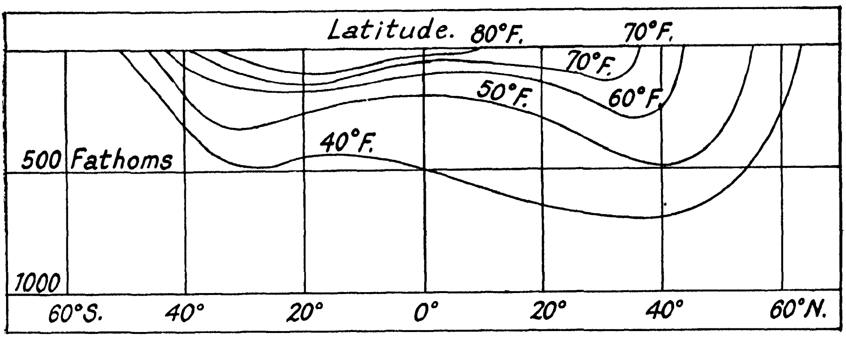


Fig. 18.—Surface Temperatures of Atlantic Ocean.

bulk of the deep Atlantic water has a temperature much below 40° F., and the warm layer is a very thin one. On each side of the equator the surface temperature falls, on an average, only one degree Fahrenheit for each hundred miles. This difference of temperature, regarded as a surface gradient, favours a surface current from the equator to the poles. As a matter of fact the abnormal pocket of warm water over the North Atlantic is due to the south-west winds of middle latitudes urging the heated equatorial water towards Europe and the Arctic Ocean.

Owing to the existence of this warm pocket it is clear that the surface temperature gradient is not the motive power causing the current, any more than is the earth's lower air temperature gradient the cause of the direction of the winds in all cases. If there were no restraining influence the warm pocket in the North Atlantic would become shallower and there would be a surface flow south towards the equator until the pocket had

disappeared. In the Southern Hemisphere this pocket is not quite so pronounced, largely owing no doubt to the width of the passage between Africa and Antarctica.

It will be convenient to consider the distribution of sea temperatures in the oceans in more detail when anticyclones and cyclones are described. The reason for this is the fact that both the winds and ocean currents are deflected by the rotation of the earth.

In this chapter only the temperature near the earth's surface has been considered. Over the oceans within the "horse" latitudes (30° to 40°) the flow is as the lower temperature gradients and the rotation of the earth demand. In the case of the atmosphere in middle latitudes, the warm winds force their way north in direct opposition to the lower temperature gradients. The denser and heavier air of high latitudes should, if surface temperatures provide the motive power, spread along the earth's surface towards the equator, as the trade-winds do. That they do not do so is a theoretical difficulty most writers on Meteorology recognise; but no satisfactory reason is given in our text-books. However it would appear that the temperature conditions of the upper atmosphere really furnish an explanation.

CHAPTER IV.

ATMOSPHERIC TEMPERATURES AND PRESSURES.

Our knowledge of the activities which result in the vertical atmospheric distribution of temperature and therefore also of pressure is very imperfect, and it is impossible to ascertain with certainty their nature and magnitude for heights exceeding those reached by sounding balloons. However it has been shown that the pressure at each point on the earth's surface is due to the weight of the atmosphere above, and that the variation between the weights of different columns is due to their varying temperatures.

When sounding balloons are employed the records of temperatures and pressures obtained at each ascent make it possible to calculate the heights of the isotherms when the barometric pressures on the ground are known. It is of the conditions existing at heights above those reached by sounding balloons, and at lower levels when the atmosphere is much disturbed, that our knowledge is most imperfect.

Until recently it had been assumed that the stratosphere was a region where the air varied in temperature from stratum to stratum only—not horizontally—consequently this upper layer of the atmosphere has been called the Isothermal Layer, and it has been supposed that in it there are no winds or vertical air currents. On such an assumption it would be necessary to infer that the stratosphere cannot affect the stability of the troposphere and alter the wind circulation therein, which is due to the varying density gradients resulting from varying horizontal temperatures. However, we now know that in the stratosphere there are strong winds and very considerable differences of temperature horizontally, and it will not be assumed that there is any level in the atmosphere the conditions above which do not affect the circulation of the atmosphere as a whole. On this account our imperfect knowledge of the temperatures in the stratosphere renders it undesirable to attempt to deal with pressures and temperatures at various heights in the troposphere as though the latter were an independent unit.

There is one active agent other than temperature which has an effect upon the pressure of the atmosphere. Newton

shewed that the weight of a substance depends upon its distance from the earth's centre. Now, owing to its rotation, the earth is caused to bulge at the equator and slightly flatten at the poles, and the result is that the earth, instead of being a true sphere, is what is known as a slightly oblate spheroid, the equatorial diameter being 26 miles greater than the polar diameter. On this account the earth's surface at the poles is nearer the earth's centre than is the surface at the equator. If a pound weight be hung on a spring, the spring will be found to stretch most in high latitudes and least in low ones. When a pair of scales is used this variation of weight with latitude is of course not shown, for the weights in both pans of the scale are similarly affected. In the case of the barometer, both air and mercury are similarly affected by change of latitude, and the barometric readings are low in high latitudes and high in low latitudes. Table III shows how much to add or subtract to get truly comparable pressures.

An aneroid barometer, which measures air pressures by means of an exhausted elastic drum, shows with considerable accuracy the air pressures arrived at by correcting the mercury barometer in accordance with the figures given in Table III.

Dr. Buchan made these corrections in his charts, and upon them most of the published maps are based. The correction, however, is not large and has little bearing upon any theoretical matters discussed in this manual. It must be pointed out that if the atmosphere were undisturbed by temperature and density differences, and were allowed to come to rest, the actual pressure differences with latitude obtained by making the correction would not give rise to air movements.

It will be seen that if the oblate form of the rotating earth produced higher pressures at the poles than at the equator, and if this difference of pressure produced continuous air movements, we should have an exhibition of perpetual motion.

The gaseous envelope of the earth, known to us as the atmosphere, covers its whole area, and submerges the highest peaks of its mountain ranges. Half of its weight, as already stated, is within four miles of the earth's surface, and it is within the lower portion of this region that the changes occur which we regard as either seasonal or fortuitous.

The difference between the weight of a bucket full of water and one empty can be appreciated by all ; but it is not so easily realised that a vessel full of air is heavier than

TABLE III.

Barometric Corrections for Latitude.

For latitudes 0° to 45° *subtract* the correction. For latitudes 45° to 90° *add* the correction.

Latitude.		Height of Barometer in Inches.								
		20	22	24	25	26	27	28	29	30
		Ins.	Ins.	Ins.	Ins.	Ins.	Ins.	Ins.	Ins.	Ins.
0°	90°	0·053	0·059	0·064	0·067	0·069	0·072	0·074	0·077	0·080
5°	85°	0·052	0·058	0·063	0·066	0·068	0·071	0·073	0·076	0·079
10°	80°	0·050	0·055	0·060	0·063	0·065	0·068	0·070	0·073	0·075
15°	75°	0·046	0·051	0·055	0·058	0·060	0·062	0·065	0·067	0·069
20°	70°	0·041	0·045	0·049	0·051	0·053	0·055	0·057	0·059	0·061
25°	65°	0·034	0·038	0·041	0·043	0·044	0·046	0·048	0·050	0·051
30°	60°	0·027	0·029	0·032	0·033	0·035	0·036	0·037	0·039	0·040
35°	55°	0·018	0·020	0·022	0·023	0·024	0·025	0·025	0·026	0·027
40°	50°	0·009	0·010	0·011	0·012	0·012	0·012	0·013	0·013	0·014

the same vessel when it is vacuous. However, it can be proved by weighing that an exhausted vessel one cubic foot in capacity is 0·086 lb. lighter than when it is full of dry air at 0·0° F. and at a pressure of 14·707 lbs. per square inch. At 60° F. the difference is only 0·076 lb., a fact which shows that as the temperature rises the air expands and becomes lighter.

The air is held upon the earth by the attractive force of gravity, just as is the water of the oceans and seas, and the movable matter on the surface. Of course the whole earth is held together by gravity ; but the force is more particularly apparent when the objects considered are movable.

At each level the air has to support the weight of the residual air at higher levels, and is in a compressed condition in consequence. The weight above and the amount of compression therefore decrease as we move from lower to higher levels, and if we look upon the atmosphere as consisting of a number of layers resting the one upon the other, it is clear that each layer by its weight compresses the layers beneath it. We thus conclude that the pressure of the air on any area at the earth's surface is due to the total weight of the air above.

The atmospheric pressure is measured by an instrument known as a barometer. In it a column of mercury (or other heavy liquid) partly fills a vertical glass tube, the upper end of which is closed, whilst the lower end dips into a bowl of mercury. The space above the mercury in the tube is nearly free from air or other gas. In no case can the space above the mercury be regarded as a perfect vacuum, for mercury itself evaporates, and its vapour pressure is always exerted. However, at ordinary temperatures the pressure of mercury vapour is very small, and can be allowed for if necessary. In the practical use of such an instrument many small corrections must be made to the readings obtained if very accurate results are desired. How to effect this can be ascertained from any work on practical Meteorology.

When the glass tube is long enough, the surface of the mercury in the tube rises as high as is possible and has practically no air pressing upon it ; but the surface of the mercury in the basin outside has the whole weight of the atmosphere pressing upon it. The weight of the mercury column in the tube standing above the mercury surface outside is therefore almost exactly equal to that of a column of the atmosphere outside, of the same diameter as the

inside of the tube, and extending to where it meets space. This experiment was first made by Torricelli in 1643 and he rightly concluded that it is the weight of the atmosphere pressing upon the mercury surface outside that balances the weight of the mercury column in the tube.

Perrier, at the request of Paschal in 1648, repeated the experiment on the top of the Puy de Dôme and found that the height of the mercury column there was three inches less than at the bottom of the mountain. It was thus proved conclusively that the barometer really does tell us what the weight of the atmosphere is.

It was soon noticed that the height of the mercury column varies from day to day and hour to hour, and it was eventually seen that many other atmospheric changes take place in sympathy with its movements. So accurately can atmospheric pressures be read, that differences of only a few feet in height can be detected easily.

In a hilly country barometers placed at different points show atmospheric pressures varying very considerably the one from the other, even though the actual pressure at sea-level be the same everywhere. On this account, for scientific purposes, it is necessary to correct the readings by an amount depending upon the height of each barometer above sea-level. All the figures given in the official weather reports are treated in this way. They are the readings each barometer would have shown had it been at sea-level.

We shall see that when proper corrections are made to the observed readings of pressure over large areas, the readings show a close connection with wind directions and to some extent with variations of temperature. In the case of great mountain ranges and plateaux, reductions to sea-level cannot be made quite so satisfactorily as in the case of moderate elevations. In all cases the correction must take into consideration changes of air density due to varying temperatures, and this temperature correction is less accurate the higher and larger the elevated area.

For ordinary survey purposes the barometer can be relied upon for observing heights above the sea. Its usefulness for this purpose depends largely upon the accuracy with which the various corrections necessary can be made. For isolated hills and districts of moderate area, very satisfactory determinations of height are possible ; but for continental areas the figures are less accurate.

Tables IV and V are given for the purpose of showing

TABLE IV.

Change of Barometer Readings with Height.

SEA-LEVEL ASSUMED AT 30 IN. $T + t = 64°$ F.

Bar.	0·0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0·8	0·9
29	886	796	706	617	528	439	351	263	175	87
28	1,802	1,709	1,616	1,524	1,432	1,340	1,248	1,157	1,066	976
27	2,753	2,656	2,560	2,464	2,368	2,273	2,178	2,084	1,990	1,896
26	3,739	3,638	3,539	3,439	3,340	3,241	3,143	3,045	2,947	2,850
25	4,763	4,659	4,554	4,452	4,349	4,246	4,144	4,042	3,940	3,839
24	5,830	5,721	5,613	5,505	5,398	5,291	5,185	5,079	4,973	4,868
23	6,942	6,829	6,716	6,603	6,491	6,380	6,269	6,158	6,048	5,939
22	8,103	7,985	7,867	7,749	7,632	7,516	7,400	7,285	7,170	7,056
21	9,319	9,195	9,071	8,948	8,826	8,704	8,583	8,462	8,342	8,222
20	10,593	10,463	10,333	10,204	10,076	9,948	9,821	9,695	9,569	9,443
19	11,933	11,796	11,660	11,524	11,389	11,254	11,121	10,988	10,856	10,724
18	13,346	13,201	13,057	12,914	12,771	12,630	12,489	12,349	12,210	12,071
17	14,839	14,686	14,533	14,382	14,231	14,082	13,933	13,785	13,638	13,491
16	16,423	16,260	16,098	15,937	15,778	15,619	15,461	15,304	15,148	14,993
15	18,109	17,935	17,763	17,592	17,421	17,252	17,084	16,917	16,751	16,587
14	19,911	19,725	19,541	19,357	19,175	18,995	18,815	18,637	18,460	18,284
13	21,847	21,647	21,449	21,251	21,056	20,862	20,669	20,477	20,287	20,099

T is temperature of lower station. t is temperature of higher station.

TABLE V.

Barometric Temperature Corrections.

SHOWING VALUES OF *K*.

$T+t$	K	$T+t$	K	$T+t$	K	$T+t$	K	$T+t$	K
40°	0·973	70°	1·007	100°	1·040	130°	1·073	160°	1·106
42°	0·976	72°	1·009	102°	1·042	132°	1·076	162°	1·108
44°	0·978	74°	1·011	104°	1·044	134°	1·078	164°	1·111
46°	0·980	76°	1·013	106°	1·047	136°	1·080	166°	1·113
48°	0·982	78°	1·016	108°	1·049	138°	1·082	168°	1·115
50°	0·984	80°	1·018	110°	1·051	140°	1·084	170°	1·117
52°	0·987	82°	1·020	112°	1·053	142°	1·087	172°	1·120
54°	0·989	84°	1·022	114°	1·056	144°	1·089	174°	1·122
56°	0·991	86°	1·024	116°	1·058	146°	1·091	176°	1·124
58°	0·993	88°	1·027	118°	1·060	148°	1·093	178°	1·126
60°	0·996	90°	1·029	120°	1·062	150°	1·096	180°	1·129
62°	0·998	92°	1·031	122°	1·064	152°	1·098	182°	1·131
64°	1·000	94°	1·033	124°	1·067	154°	1·100	184°	1·133
66°	1·002	96°	1·036	126°	1·069	156°	1·102	186°	1·135
68°	1·004	98°	1·038	128°	1·071	158°	1·104	188°	1·137

T is temperature of lower station.
t „ „ higher „
Temperatures are given in degrees F.

the actual effects of height above the sea on pressure, and also the corrections required on account of the temperature of the air. Assuming that the barometer at sea-level stands at 30 inches of mercury over some large area at sea-level, then Table IV gives the heights in feet corresponding to various barometric pressures measured in a balloon floating over the area. It gives fairly correct results when the temperature, *T*, of the lower station and that of the higher station, *t*, are equal to 64° F. when added together. To correct for other temperatures Table V must be used, and the heights given in Table IV must be corrected by multiplying them by the figures for *K* given in Table V. The figure so obtained is the difference of level between the two stations selected.

The main source of error in this method of measuring heights is that the pressure at sea-level is never the same all over any large area, and also is continually undergoing change. On this account the farther the points of observation are apart the more serious the error may be.

It is well to remember that the temperature at which

water boils varies with changes in the pressure of the atmosphere, and heights consequently may be ascertained from determinations of this boiling-point. The decrease of pressure with altitude lowers the boiling-point, the fall being approximately 1° F. for each 555 feet. When two observations of the temperature of ebullition are made, one at the foot of a mountain and the other on the top, the difference between the boiling-points in degrees F. multiplied by 555 gives the difference in the heights in feet.

Since water vapour is lighter than dry air in the proportion of 62 to 100, air containing water vapour is lighter than dry air. Corrections for its presence, however, are small and are rarely made, as the proportion of water vapour present is small. In Chapter V the rôle played by water vapour in the atmosphere will be considered in some detail.

We have seen that the density of the atmosphere varies owing to differences in temperature, pressure and humidity, and these are so intimately connected that it is difficult to consider the one without the other.

Most forms of matter may exist in three states, depending upon the temperature and pressure, viz. as solid, liquid or gas. The distinguishing feature of gases is their power, when free from constraint, of indefinite expansion. In the case of the atmosphere, gravity prevents indefinite vertical expansion, and therefore prevents it from entirely escaping into space. All gases with greater or less degrees of accuracy fulfil certain numerical laws known as the Gas Laws. These are:—

Law I.—The pressure of a gas is proportional to the density.

Law II.—The volume of a gas, under constant pressure, increases when raised through the same temperature interval by the same fraction of itself, whatever be the nature of the gas.

These two laws may be combined into the statement that—

The volume of a gas multiplied by its pressure is proportional to the *absolute temperature*.

What is absolute temperature? The temperature of a body is lowered by abstracting heat from the body, not by adding cold. We wrongly say that "the frost has got into it." This statement is quite incorrect and utterly misleading; for the higher the temperature of any particular substance

the more heat there is in it, and the lower the temperature the less heat. Frost is that state of temperature of the air which causes water to freeze, and when the temperature is such that water becomes solid it is said to be "frosty." That there are two generally recognised temperature conditions, the one cold and the other warm or hot, means only that the one we call "cold" feels cold to the touch and the other we call "hot" feels hot to the touch. But water that feels cold to a warm hand may feel warm to a cold hand. The only satisfactory way of measuring the temperature of a body is by using a thermometer. If the body is warmer than the thermometer in contact with it, heat flows into the mercury, which expands, and the thermometer reading rises until the mercury temperature is the same as that of the body in contact with the thermometer. On the contrary, when the body is colder than the thermometer, heat passes from the mercury to the body in contact with it, and the mercury contracts until the temperatures are again equal. Now it is clear that a substance can only contain a certain quantity of heat, and as this is removed the temperature falls, so that when all the heat has been abstracted the *absolute zero* of temperature is reached. No further cooling is then possible.

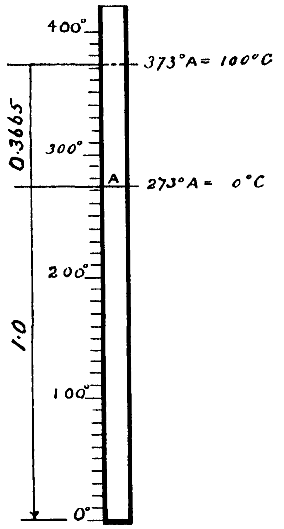


Fig. 19.—Absolute Air Thermometer.

It is found that if a gas be cooled it is possible to ascertain the absolute zero of temperature by observing the rate at which it contracts. Suppose the glass tube of Fig. 19 be full of dry air. At the point *A* is a very light well-fitting piston, the movement of which up or down enables us to ascertain what volume the air occupies at different temperatures. When the tube is surrounded by broken fragments of ice the piston stands at 0° C. This is the freezing-point of water. Now let the ice be removed and the tube be surrounded by steam, the barometer standing at 29·925 inches of mercury. The piston now rises to the position 100° C., the boiling-point of water at 29·925 inches. We now divide the space between the freezing- and boiling-points into 100 parts, and we have an air thermometer which gives temperatures according to the Centigrade scale. If we had made the freezing-point 32° and the boiling-point

212°, it would have been a Fahrenheit thermometer. Careful experiment has shown that the same quantity of heat is always required to raise the temperature from one mark to the next above, and it has been ascertained that if we continually abstract equal amounts of heat from the air in the tube the temperature will go on falling at the same steady rate, all the divisions below the freezing-point being equal to those above. It is clear that if we went on cooling the air at this rate the piston would eventually reach the bottom of the tube and the air would have disappeared. To determine the reading at the bottom of the tube is an easy matter. We know that the distance of the freezing-point from the bottom of the tube is to the distance of the boiling-point from the bottom of the tube in the proportion of 1 to 1·3665, since this is the increase in bulk of air between the freezing and boiling temperatures. Hence it follows that if the freezing-point is marked 0°, and the boiling-point 100°, the bottom of the tube must be marked −272·85°. We thus conclude that at about −273° below zero Centigrade we have reached the absolute zero of temperature. Counting the divisions from the bottom of the tube, the freezing-point is 273° C. absolute and the boiling-point 373° C. absolute. These temperatures are now written 373° A., etc.

In the case of a gas, the pressure remaining constant, when we reduce the absolute temperature to one half, the volume is also reduced to one half. Similarly when we reduce the absolute temperature to one quarter, the volume is reduced to one quarter also.

Soon after the invention of the barometer great interest was aroused by the discovery that the pressure of the air is everywhere continually changing ; but it was not until records from numerous stations, properly reduced to sea-level and plotted upon charts, were studied that the nature of the variations became clear. It is necessary to take care that all the observations required for a chart are made at the same moment, if one is to obtain a true idea of the conditions obtaining at any particular time. Each pressure is marked upon a map in its proper position. When this is done it is found possible to draw between the figures lines of equal pressure, called *isobars*, and having done this it is found that there are areas of low pressure surrounded by areas of higher pressure. Such a drawing is called a *synchronous chart.*

Fig. 106 is such a synchronous chart of the area around the North Pole for January 10, 1930. The isobars are four

millibars apart. (*L*) indicates low pressures and (*H*) high pressures. Here we have an enormous area of low pressure with three eyes (*L*) centred over Spitzbergen, Iceland and South Greenland, and another large low pressure area centred over the Behring Sea. Over the greater portion of North America the pressure is high, as it is also over Central Asia and Southern Europe.

Other maps or charts have had plotted upon them the mean pressures for each month instead of the pressures for some particular instant of time. Fig. 104 shows the mean pressures for January, 1930, over the North Polar area. From this we see that during that month the pressure over a very large area centred near Iceland was low, the higher pressures being over North America, Central Asia and mid-Atlantic.

Low-pressure areas are cyclonic in character, the winds circulating round their centres according to definite laws.

The foregoing charts resemble in some respects contoured land surfaces, lowlands resembling high-pressure areas, and hills low-pressure areas. However, although this resemblance is noticeable, low-pressure areas are called " depressions " or " cyclones " and are referred to as " deep " or " shallow " as the case may be, whilst high-pressure areas are called " anticyclones," and are referred to as " ridges " of high pressure when they are not compact. It must be remembered that the isobars (lines of equal pressure) have been drawn from observations which have been reduced to sea-level, and that the low pressures are not due to any varying thickness of the atmosphere, but to differences of density resulting from the differences of temperatures at various levels.

From what has previously been stated, it is evident that if the sea-level pressures were uniform over a large area of relief, and the pressures obtained at different levels were plotted, the isobars would be actual land contour lines, showing the positions and depths of valleys and the heights of mountains. It is this consideration that is taken advantage of to ascertain heights by means of barometric measurements. The similarity of an isobaric chart to a contoured land surface chart has caused meteorologists to speak of cols, pressure ridges, low-pressure troughs, etc. However, the similarity fails somewhat when we come to cyclones and anticyclones, for, as already stated, the contours of a mountain generally resemble the isobars of a cyclone more than the isobars of an anticyclone.

Fig. 20 represents a portion of a large cyclone covering a given area, and Fig. 21 the same area having three small cyclones over it. When these two charts are combined, the isobars run as shown in Fig. 22. It would seem that the main features indicated by isobaric charts can be accounted for by regarding them as being due to the combination of a number of approximately circular cyclones of different

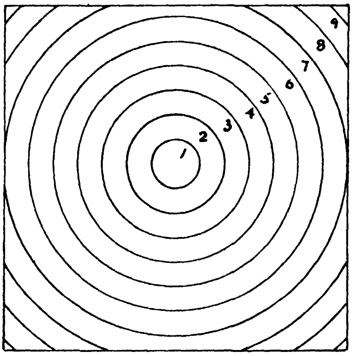


Fig. 20.—Isotherms of Ideal Primary Depression.

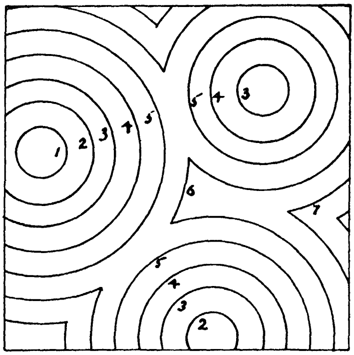


Fig. 21.—Isotherms of Three Ideal Secondary Depressions.

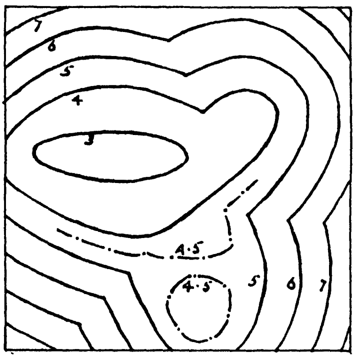


Fig. 22.—Mean Isotherm Chart.

diameters separated by high-pressure areas. Large stationary cyclones are often associated with settled weather, except in mountainous regions, but when the isobars run irregularly as a result of the presence of numerous small cyclones, the weather is unsettled.

Isobaric charts thus are of several kinds. Some show the mean pressures over considerable intervals of time, such as mean annual or mean monthly pressures, whilst others are synchronous, and show the pressure conditions at particular moments over large areas. Then we have

charts showing, for particular areas, the departure from the means for longer or shorter periods. Perhaps the most useful are the synchronous isobaric charts, such as are issued regularly by the Meteorological Office. They are drawn for stated times each day, and enable us in many instances to see the changes that take place with the lapse of time in the pressures and positions of high- and low-pressure areas. In some cases they are not able to do this very clearly, for the changes are so rapid that three or four charts each day would be required to show what really was taking place.

Figs. 23, 24 and 25 show the progress of a cyclone which crossed slowly over Ireland and England to the North Sea on August 19, 20 and 21, 1931. On the 19th the pressure

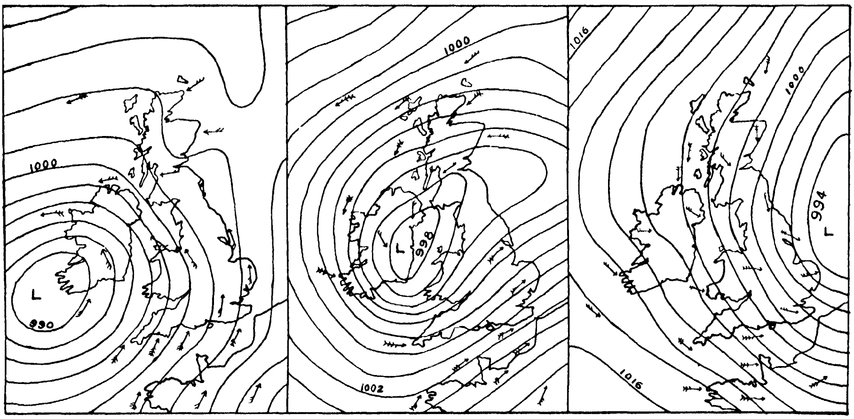


Fig. 23. Fig. 24. Fig. 25.

Movement of Travelling Depression.

was 990 mbs. near the centre, about 998 on the 20th, but on the 21st had fallen to 994. The arrows are supposed to fly with the wind, and they show that the air circulation was in accordance with Buys Ballot's law, viz. counter-clockwise.

Much has been written concerning the mass movements of travelling cyclones. Do they move with the mass of surrounding air ? Or do they carry along with them small masses of air as does a smoke ring ? Or do they involve fresh air in their fronts, then involving this in their internal movements, leaving behind them air which at one time took part in their whirling motions ? These are important questions, but are too complex a matter to deal with until cyclones come to be treated in more detail.

If the air moved in a direct course from areas of high to areas of low pressure, it would palpitate about the low-

pressure centre until its viscosity damped down the motion. As a matter of fact, the air circulates around the low-pressure centre in the form of a great whirl or cyclone, and the centrifugal force due to its velocity, and the effects of the earth's rotation, tend to cause it to persist until its viscous friction and that of the ground, etc., and loss of heat, stop it. Where the gradients of pressure are steepest the winds are strongest. The consideration of the part played by the rotation of the earth in anticyclones and cyclones is very complex, and its detailed treatment will also have to be postponed until the theory of cyclones comes up for consideration. Buys Ballot's law concerning the circulation of the wind in cyclones in the Northern Hemisphere is as follows:—" Stand with your back to the wind, and the barometer will be lower on your left hand than your right." The reverse is the case in the Southern Hemisphere. This is perhaps the most important of all meteorological generalisations.

It is largely to the disturbing effect of such cyclones that most weather changes, other than seasonal, are due, and it is often impossible to anticipate what the lapse of a few hours will result in. In England cyclones generally travel from west to east, seldom from east to west. However, they do sometimes move from north to south or even *vice versa*.

Considering the increasing angle of the sun's rays as we move to higher latitudes, both north and south of the equator, and the nearly overhead position of the sun in equatorial regions, the growing cold as we approach the poles does not excite our wonder. However, from what has been said concerning the effect of cold in increasing the density of the air, we should naturally expect to find atmospheric pressures greater in high than in low latitudes. The peculiar circumstance is that areas of low or high pressure are not peculiar to regions of high or low ground temperature. The polar areas are regions of low pressure and low ground temperature, whereas the equator is a low-pressure area but has a high ground temperature. On each side of the equator, between latitudes 30° and 40°, run two high-pressure and moderate ground temperature belts, which retain their identity with considerable regularity over both oceans and low lands.

It is well to recognise fully that the charts of pressure reveal characters of a very unexpected nature in their broader aspects. This matter will receive very careful treatment when the theory of the winds comes up for con-

sideration. We shall then see that the general circulation of the atmosphere, and its varying pressures, are in agreement, but that the surface temperature gradients of the earth do not reflect the temperature conditions of the mass of the atmosphere.

Early in the present century a prominent German meteorologist remarked that the temperatures in the interior of cyclones and anticyclones up to considerable altitudes are such that it is impossible to explain the existence of these disturbances as being due to the specific weight of the central column of air, and that one is inevitably led to explain them as the result of the influence of the general circulation. Now the general circulation is itself cyclonic, and presents the same features as the smaller disturbances, and we may well ask where do the large cyclones obtain their energy if the smaller ones obtain theirs from the larger ones?

It is not necessary to reject the theory that it is the high temperature and light weight of the central column of air that causes the low pressure and maintains the circulation, until we know what are the temperatures of the air up to the limits of the atmosphere. There are those who argue that there can be no vertical movements of the air in the upper atmosphere. This is quite incorrect, for it has been pointed out that meteor tracks often remain visible for considerable intervals of time and show by their distortions that the upper air often moves rapidly and irregularly.

Synchronous charts of the whole earth are not available, and our knowledge of the daily variations of pressure taking place in the North Polar regions is of very recent date. However, the daily charts now issued for a large portion of the Northern Hemisphere by the Meteorological Office, give a good deal of very valuable information. Many of these synchronous charts are so complete that we now have a good idea of how pressures vary from day to day in high northern latitudes.

These charts will be more fully dealt with when the circulation of the atmosphere comes up for consideration. To compare the pressure gradients of the Northern and Southern Hemispheres it will be necessary to use less recent figures.

Table VI shows the mean annual pressures along latitudes in both hemispheres. In latitudes 80°, 75° and 70° N., that is in the neighbourhood of the North Pole, a slightly higher pressure is shown than occurs immediately to the south. However, when the table was compiled very little

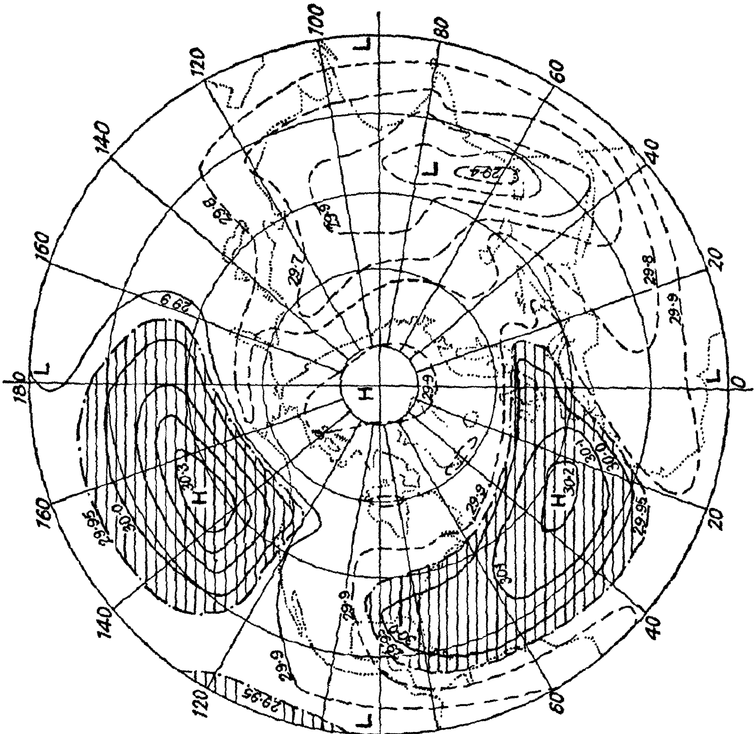
was known of the prevailing pressures in these high latitudes, but we are now aware that such conditions often prevail. The most striking feature of the table is the low pressures of the polar areas as a whole. It has been explained that the higher the barometer the heavier the air column above it. At the Equator the mean pressure is 1010·7 millibars. As we move north and south from it the pressure rises until 35° north and south latitudes are reached. Here the pressure

TABLE VI.

Variation of Mean Annual Temperatures and Pressures, and Percentage Land Areas, with Latitude.

Latitude.	Northern Hemisphere.			Southern Hemisphere.		
	% Land.	Press.	Temp.	% Land.	Press.	Temp.
Equator	23	1010·7	79·9	23	1010·7	79·9
5°	23	1010·7	81·0	23	1011·1	79·7
10°	24	1010·5	80·0	23	1012·0	78·2
15°	25	1011·1	79·5	23	1013·6	76·0
20°	32	1012·3	76·9	23	1015·3	73·9
25°	40	1013·9	73·3	22	1017·6	69·1
30°	42	1015·6	68·4	18	1018·0	64·9
35°	44	1016·5	63·3	10	1016·5	59·6
40°	47	1016·0	57·1	5	1014·0	54·0
45°	51	1015·3	50·3	4	1009·3	48·3
50°	55	1014·3	42·5	2	1004·3	41·5
55°	60	1012·9	36·0	1·5	997·6	36·0
60°	64	1011·6	29·8	1	991·2	30·0
65°	66	1010·9	21·0	0	986·3	...
70°	54	1011·5	13·7	0	984·0	...
75°	32	1013·0	7·4			
80°	24	1013·9	1·6			

is 1016·5 millibars. This increase of pressure is such as we should expect, for it is reasonable to suppose that as we reach higher and higher latitudes where the sun is low even at midday over long periods of the year, the air column is colder and therefore heavier. It is not at all likely that the atmosphere is thinner where the pressure is lowest. Although the pressures in both hemispheres are the same for lat. 35°, in the southern area the pressure reaches 1,018 mbs. in lat. 30°. As we go north and south from these two bands of high pressure which encircle the earth, pressure falls again. In the Northern Hemisphere at lat.



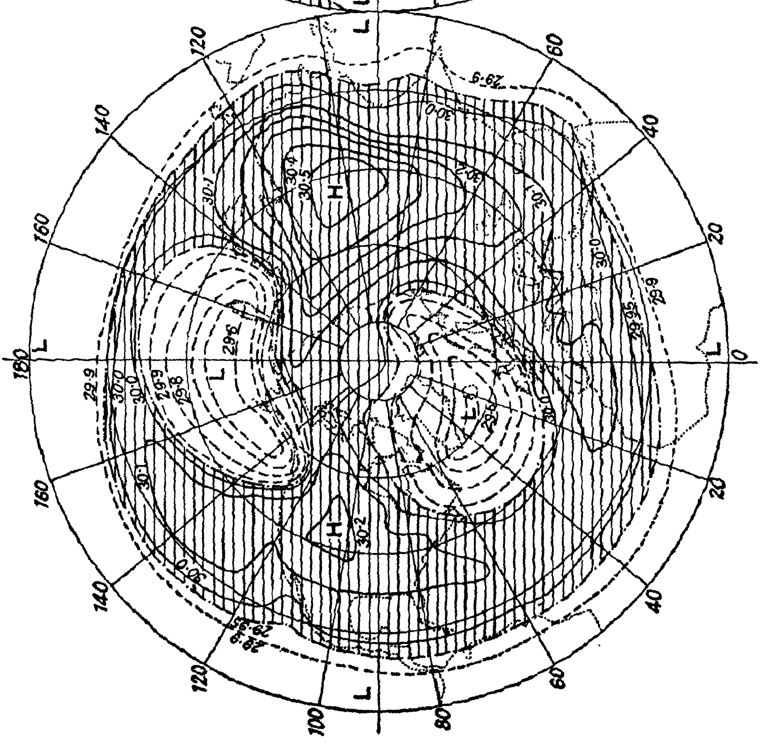


Fig. 26.—Mean January Isobars of Northern Hemisphere. Fig. 27.—Mean July Isobars of Northern Hemisphere.

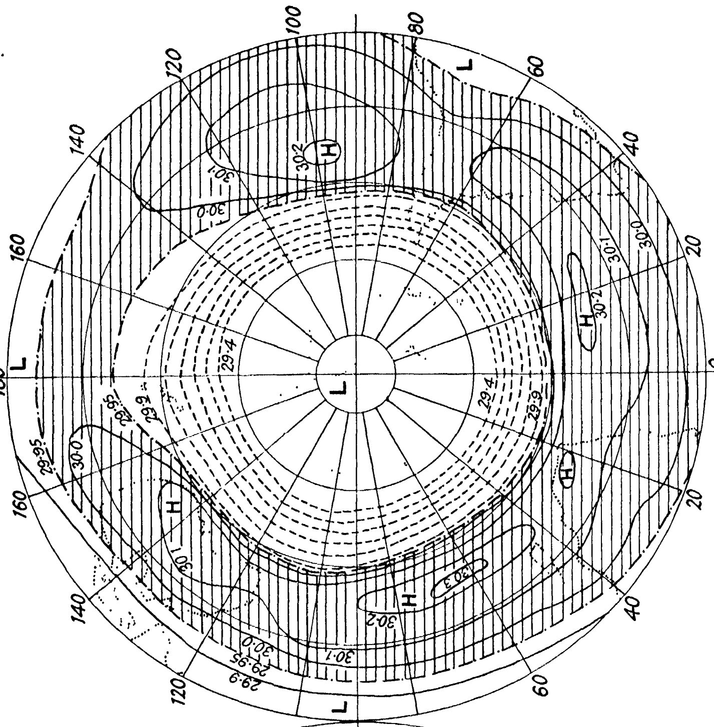
(After Buchan.)

70° it is 1011·5 mbs., and in the Southern Hemisphere in the same latitude it is 984 mbs. This decreasing pressure as we pass into colder climates has given rise to much discussion ; for it is known that as we go polewards from the high-pressure belts the masses of air at similar levels forming the lower atmosphere (troposphere) become colder and therefore heavier, and we must either suppose that the atmosphere in high latitudes is either thinner than in low latitudes, or that the upper atmosphere in high latitudes is very much warmer. This problem has greatly puzzled meteorologists ; but of recent years much has come to light concerning high-altitude conditions, and this information has been extremely helpful. When the theory of cyclones comes up for treatment the matter will be fully discussed.

The variations of pressure with latitude as well as longitude can be exhibited only by charts, and Figs. 26, 27, 28 and 29 have been drawn to show the average pressure conditions on the earth for January and June in the Northern and Southern Hemispheres. From Table VI we gather that the great difference between the two hemispheres is the greater proportion of land in the north. Not only is there a much larger area of land north of the equator than to the south, but there are great ranges of mountains and high plateaux both in Europe, Asia and North America. A glance at the charts reveals the startling effect this has on the pressure distribution of the two hemispheres. Areas where the pressure is high have been hatched horizontally so as to make them easily seen.

In July (Fig. 27) two high-pressure centres exist in the high-pressure belt between latitudes 30° and 40° North, one over the Pacific Ocean and the other over the Atlantic. Over North America the pressure is low, whilst over portions of Asia it is very low, the low-pressure centres being over the high plateaux and mountain ranges. In January the pressure distribution is very different, the high-pressure belt being further north and forming a complete band round the earth, the highest pressures being over the land areas, especially over Central Asia. However, over the North Pacific and North Atlantic are two very low cyclonic areas, which seem quite out of place so near the Arctic regions.

In the Southern Hemisphere the influence of land is very much less pronounced, and very low pressures indeed characterise the cold Arctic seas. January being summer in the south, the pressures are lower along the southern high-pressure belt than over the northern one. In winter (July)



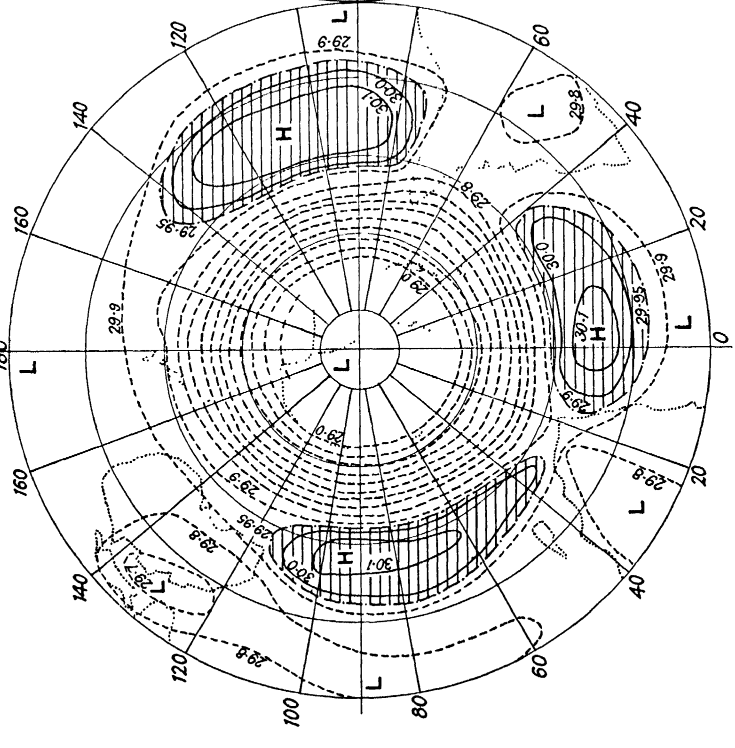


Fig. 28.—Mean January Isobars of Southern Hemisphere. Fig. 29.—Mean July Isobars of Southern Hemisphere.

(After Buchan.)

(Fig. 29) this high-pressure belt is continuous, but of varying intensity.

The remarkable feature of both Figs. 28 and 29 is the great cyclone over the Antarctic Continent and cold southern seas, and the pronounced anticyclonic belt over the warm equatorial seas in July. The depression has a diameter of about 3,500 miles, and persists the year through.

It must be remembered that these charts are not synchronous charts. They show the average monthly conditions. Synchronous charts of the same area, such as are available, show a general decrease of pressure as the pole is approached ; but they show in addition numerous secondary cyclones moving from west to east. It is these secondary cyclones which give variability of climate with latitude.

The Antarctic cyclone is not a secondary result of the general circulation. It is actually an important part of the general circulation, and we must regard the prevailing winds as being due to the combined effect of the upper atmosphere (stratosphere) and the lower atmosphere (troposphere).

The three southern and two northern summer high-pressure areas on the high-pressure belts are over the cool oceans. The winter high-pressure area over Asia is evidently the result of the cold of the high mountain regions between latitudes 50° and 55° N. The lowest pressure of the equatorial low-pressure belt extends from Central Africa over India and the Malay States to long. 165° E.

If we had to deal solely with the area about 40° north and south of the equator we should see that the pressure gradients are closely in agreement with the temperature gradients, but modified somewhat by the cooling effect of the great oceans and the heating effect of continental areas of comparatively low relief. In the Southern Hemisphere the high-pressure belt during the winter has five areas where the pressure is high and where anticyclonic conditions are most pronounced. The most marked are over the Pacific, Atlantic and Indian Oceans, and the less marked over Australia and Africa. In the summer the three oceanic high-pressure areas remain ; but those over Southern Africa and Australia have disappeared owing to the heating of the land. In the Northern Hemisphere the high-pressure belt during winter is greatly influenced by the land masses, over the cold surfaces of which the highest pressures prevail. However, the high-pressure belt is continuous, and there is a large high-pressure area over the Eastern Pacific. In the summer all the continental areas show low pressures,

and the anticyclones over the Pacific and Atlantic are very marked.

Polewards of the high-pressure belts the departure of pressures from what might be expected from the temperatures of the lower atmosphere is, as already stated, very marked indeed. Table VI shows this clearly. From the equator the pressure rises to 1,016 mbs. at 40° lat. and the temperature falls from 79·9° to 57·1° F. This is for the Northern Hemisphere. In the Southern Hemisphere the pressure rises from 1,010·7 mbs. to 1,018 in lat. 30° and the temperature falls from 79·9° to 64·9° F. In the Northern Hemisphere both the temperature and pressure fall to lat. 65°, whilst in the Southern Hemisphere the temperatures and pressures also both fall and it would appear that the fall extends beyond lat. 60°. When we come to consider the winds we shall find that in middle latitudes they too largely ignore surface temperature gradients in the troposphere (lower atmosphere).

It is interesting to compare a little further the temperature gradients of the Southern Hemisphere with those of the Northern. In the equatorial low-pressure belt the temperatures are somewhat lower to the south of the equator than they are to the north, for the southern area is less land-locked. Now when comparing temperatures over land and sea along similar latitudes, we saw that the oceans in summer were cooler than the land areas, and on this account we might expect the annual temperatures of the Southern Hemisphere to be lower than the Northern. It would appear that the comparatively high temperatures of the southern oceans is due to the fact that the lower-level warm winds of the tropics blow spirally towards the centre of the Antarctic cyclone, and thus keep the southern seas at about the same temperature as the northern ones, in spite of the ice of the Antarctic Continent and oceanic conditions.

The charts illustrating surface temperatures and pressures so far have been concerned with the mean annual and January and July conditions. Each year, however, has its peculiarities, and so have each summer and winter and even each day. This is especially the case in middle and high latitudes. In low latitudes the weather is usually moist, warm and equable, the average temperature being in the neighbourhood of 80° F. The rainfall is frequent and heavy, especially over water and land areas on the side from which the wind blows. In middle latitudes the weather is unsettled, and there are great and variable changes in temperature, moisture and rainfall from day to

day and season to season. In high latitudes the average temperature is below the freezing-point, rainfall is scanty, the summers short and the winters severe ; storms are somewhat infrequent in the summer, but common in the winter.

There is also a marked difference between oceanic, insular and continental climates. Over the oceans the temperature generally is equable, moisture is considerable and rainfall more frequent than the want of relief would lead us to suppose. In continental areas the day temperature is high and the night temperature low, the difference being most marked where the sky is clear and the rainfall small ; rainfall and temperature are subject to great variations, and there is a general tendency to extremes in all climatic elements. Insular and littoral climates partake alternately more or less of the characteristics of both oceanic and continental weathers.

In the British Isles, where the general drift is from the west, the climate generally is oceanic. When it blows from the east it is continental. Sometimes the general circulation largely dies down and we get mixed weather depending upon the relative positions of high- and low-pressure areas of a local nature.

Europe has in recent times suffered from extreme continental and also from extreme oceanic conditions. Indeed, if cold spells, such as have many times occurred for short periods in recent years, were to be lasting, or of more frequent occurrence, the climates concerned would be greatly affected. On this account the conditions which were responsible for the extremes are of extreme interest to the meteorologist.

December, 1879, was one of the coldest Decembers of recent times, and December, 1880, was one of the warmest, 1879 being at the bottom of a sunspot cycle trough and 1880 the first year of the next wave. Both these cases have the advantage of being comparatively recent, and they have been carefully studied. The difference between the mean temperatures of the two months in Central Europe amounted to 12° to 14° C.

The extraordinary cold spell of December, 1879, was accompanied by high pressures, clear, still, cold air, and ground fog. It was just the same sort of weather that is experienced every winter in a much more intense form around the Verkoyansk centre of cold in Siberia. Snow fell over a wide area and covered all Central Europe as far south as Northern Italy with a thick coating. The

pressure conditions prevailing during December, 1879, and December, 1880, are shown in Figs. 30 and 31, respectively, and the temperature conditions in Figs. 32 and 33,

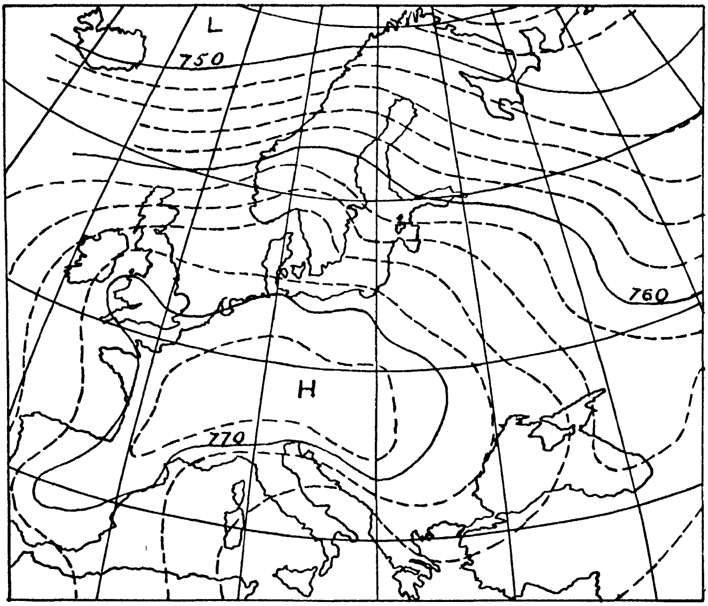


Fig. 30.—European Isobars of December, 1879.

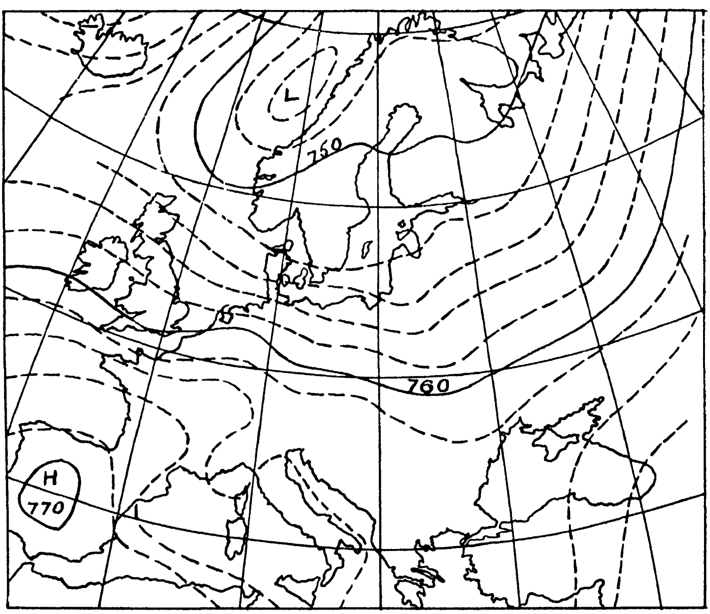


Fig. 31.—European Isobars of December, 1880.

respectively. The low-pressure area in 1879 lay exceptionally far to the north and east, and the ocean winds were strongest in Northern Europe, where although the air was warmer

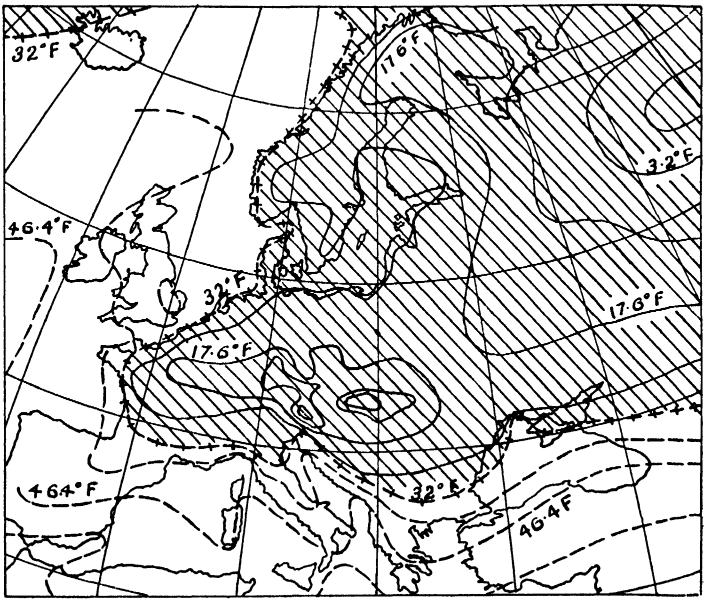


Fig. 32.—European Isotherms of December, 1879.

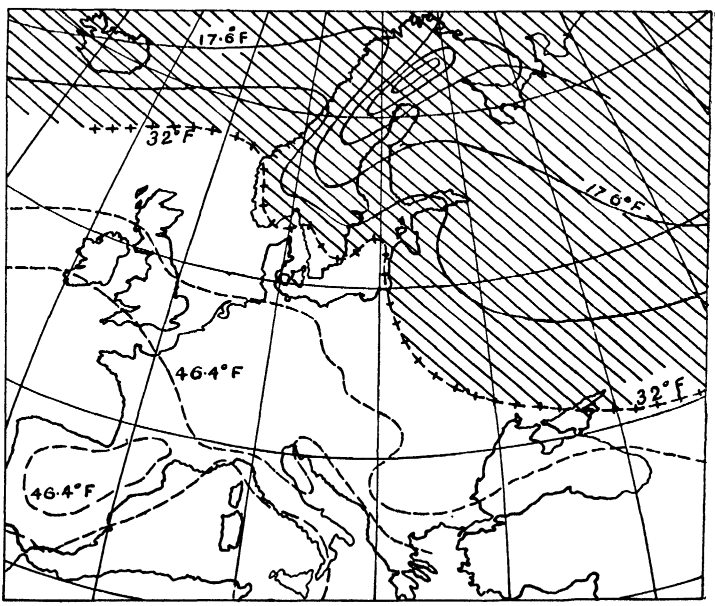


Fig. 33.—European Isotherms of December, 1880.

than usual, the temperature did not rise above 32° F. In Central Europe the winds were local or continental, the minimum temperature fell as low as 10° F., and even lower in many districts of south-west Germany. The isotherm of 32° F. is seen to surround the whole body of Europe.

The following December, 1880, was, however, quite different. Figs. 31 and 33 show the isobars and isotherms for this month. An area of low pressure covered North and Central Europe. The pressure conditions were favourable for the flooding of Central and Western Europe with warm moist air from the Atlantic. The winds came from the south-west and west, and brought in their train great humidity, clouds and rain.

The conditions during the Decembers of these two years will be remarked upon again when we come to consider climatic variations. During the cold spell the North Polar cyclone was comparatively inactive, whereas during the warm winter it was deeper than usual.

CHAPTER V.

WATER VAPOUR, TEMPERATURE, AND PRESSURE.

WATER vapour has been treated in Chapter II merely as a constituent of the atmosphere. We must now consider some of its physical properties and call attention to the important part it plays in meteorological phenomena.

Although the most interesting meteorological characteristics of water are shown in its vaporous condition, it is interesting in all its physical states. In its liquid condition it occupies about three quarters of the earth's surface, and owing to the vapour it gives off, and its high specific heat, the rôle it plays in determining climate is very important indeed. Some writers, in the author's view, unduly discredit the heat-carrying capacity of ocean currents and ocean drift. This being an important question in Meteorology it deserves more consideration than it usually receives.

When describing the method of determining the absolute zero of temperature the air thermometer (Fig. 19) was referred to, and it was explained that it has been found by experiment that equal increments of heat must be communicated to this thermometer to raise the column of air equal distances. Different liquids, gases and solids require different amounts of heat to raise them one degree in temperature. The specific heat of solids is not a very important factor, however, in Meteorology ; but the reverse is the case with gases and liquids. The specific heat of any substance is the quantity of heat required to raise unit weight of the substance one degree in temperature as compared with the quantity of heat required to raise unit weight of water one degree. But the quantity of heat required to raise one pound of water one degree is not quite the same at all temperatures. It is usual to consider as the unit (one calorie) the amount of heat required to raise one gramme of water from 4° to 5° C., 4° C. being the temperature of water at its greatest density. Now the specific heat of air when it is free to expand is only 0·2375, water being 1·0. A column of dry air equal in weight to that of the whole atmosphere requires only as much heat to raise it one degree in temperature as would raise 7·4 feet

of water one degree in temperature, the sectional areas being the same.

Now ocean drift, and ocean currents, such as the one flowing out of the Gulf of Florida, are hundreds of feet thick, and, owing to the high specific heat of water, carry vastly greater stores of heat with them than does the whole atmosphere above. In very many cases the ocean currents are running in opposition to the water temperature gradients. Indeed it has been shown that the temperature gradients of the oceans are often in direct opposition to what we should expect from the manner in which insolation varies with latitude. On this account it is inferred that ocean currents and drift are in many instances clearly caused by wind friction on the seas, not by variations in water density, and the fact that, as a rule, ocean currents and the prevailing winds flow together as closely as land barriers will permit, need not seem strange. In many instances we have cold Arctic and Antarctic winds moving into warmer latitudes. In such cases the cold ocean water prevents the increasing insolation from warming the air, and such ocean winds are cold or cool even in the summer.

Practically all substances which are not dissociated by heat can exist as solids, liquids and gases, if the temperatures and pressures are suitably arranged. In the case of water, the solid state is a peculiar one, for often when it consists of countless crystal grains, such as it does in glaciers, it behaves as a very viscous liquid. We shall have to be content at present with using the word "solid" in a rather loose manner. No doubt the time will come when the various states of matter will be more clearly recognised and defined than they are now. For our present purpose crystalline ice may be regarded as a solid, but when such crystalline grains are combined to form an aggregate the mass has some of the properties of a liquid.

That glacier ice consists of countless grains of ice all firmly frozen together can be seen by examining the ice blocks which have been brought down by avalanches and have come to rest at such great heights that they evaporate rather than melt. The grains can also be seen in the caves that are often cut into glaciers for tourists to see. Figs. 34 and 35 are pencil rubbings made on the walls of an artificial cave in the Rhone Glacier. They show the beautifully lined surfaces of the crystals of which the glacier is built up. They are formed by alternating furrows and ridges along the twinning planes of the distorted crystals, due no doubt to the effects of twinning on the rate of evaporation of different

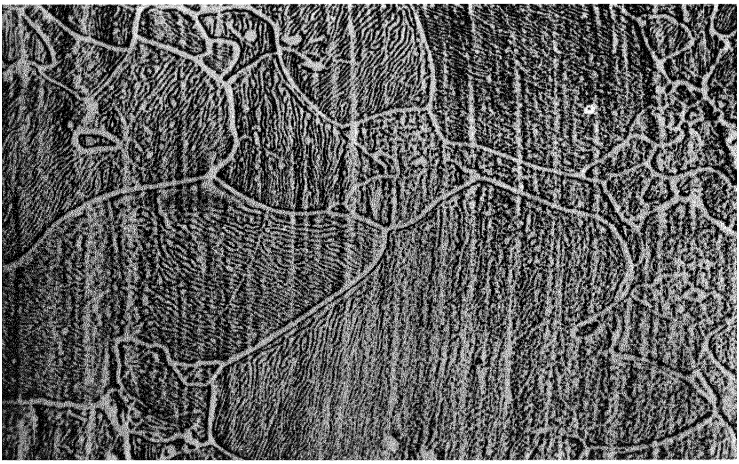


Fig. 34.

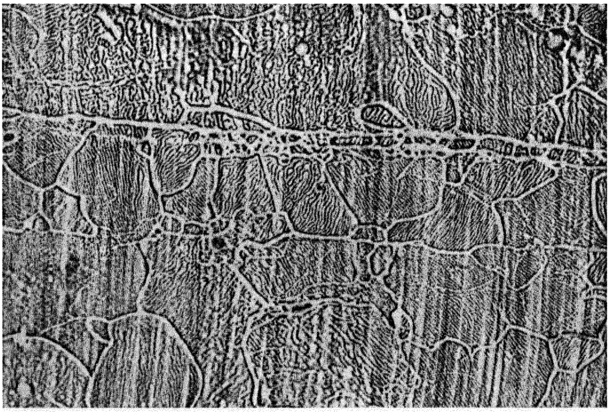


Fig. 35.

Pencil Rubbings of Glacier Ice Surface showing Situation of Grains.

portions of the surface. Evaporation has taken place most rapidly between the crystals, forming comparatively wide channels between them. In Fig. 35 it will be noticed that the mass of the ice has been sheared, and the crystals cut across and displaced, owing to the flow of the glacier.

If there were no gases in the atmosphere other than water vapour, evaporation in low latitudes would be extremely rapid and condensation in high latitudes correspondingly great. Indeed, there would be a rapid flow of water vapour from the equator to the poles, and rapid condensation on cool surfaces as well as much rain. Such an atmosphere would certainly be thin, for the water vapour as it formed would rise rapidly, chill and condense. The difficulty of predicting what the conditions would be is aggravated by the fact that we do not know for certain what the corpuscular radiations which affect the upper atmosphere are. There is every reason to believe that the air at high levels is warm and that it is heated in some way by radiations other than those of light and heat from the sun. Would a pure water vapour atmosphere be warmed at its upper limits in the same way? It is to be presumed that it would.

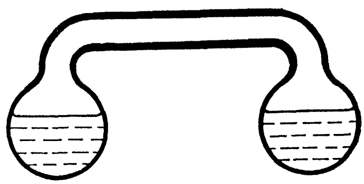


Fig. 36.—The Cryophorus.

A simple experiment shows how quickly water evaporates, how rapidly its vapour flows, and how quickly it condenses again in the absence of the admixture of air. Fig. 36 shows what is called a cryophorus. Two bulbs, partly filled with water, are connected by a glass tube, the space above the water being free from all gas except water vapour. If either bulb be immersed in very cold water or a freezing mixture, the water vapour in that bulb is condensed and fresh vapour, given off by the other bulb, flows in and in its turn condenses. Evaporation from the bulb which is not cooled may be so rapid that the water boils and eventually freezes in it if the temperature falls low enough. Even if the water be frozen in both bulbs the evaporation will be from the warmer ice and this vapour will condense on the colder ice.

The presence of an atmosphere largely composed of gases which do not liquefy with the varying temperatures such as exist on the earth, reduces the rate of evaporation of the water, and checks the transfer of water vapour from warm to cool areas. We really have two atmospheres,

the one which merely contracts with cold and expands with heat without assuming either the liquid or the solid state, and the other of water vapour which may condense to the liquid or freeze solid. All the gases given in Table I belong to the first category and remain in the gaseous state under all atmospheric conditions of temperature and pressure. Water vapour is universally present, but forms only a comparatively small and extremely variable proportion of the air. It exercises a profound and far-reaching effect on weather, and is largely responsible for the production of the beautiful cloud and colour effects, which render the sky so interesting and beautiful.

What is called the *law of partial pressures* has already been referred to. If we have an airtight vessel partially filled with water, and all the gases of what we have called the stable atmosphere are removed, a certain amount of water evaporates and fills the available space not occupied by liquid water ; a suitable gauge enables the pressure of the vapour to be read off. At low temperatures the pressure will be found to be very small. However, as the temperature rises the pressure increases, and when the pressure reaches what is called one atmosphere (29·925 inches of mercury or about 1,013 millibars) the water and steam are at the boiling-point. In Table II the pressures of water vapour, expressed in millibars, have been given for temperatures between $-30°$ C. and 100° C. At 100° C. the pressure is about 1,013 millibars. In the open atmosphere, water at this temperature boils off as steam and the temperature and pressure do not rise any higher, as long as boiling goes on.

If, when the closed vessel is at a temperature of 40° C. and the pressure 73·18 millibars, dry air at 40° C. be admitted, and time be given for the vapour and air to mix, and for the temperature to assume a steady state of 40° C., we shall find that the pressures in the vessel are as follows:—

Water vapour, . .	73·18	millibars.
Air, ...	939·82	„
Total, . . .	1013·00	„

We thus see that the law of partial pressures means that when water is in contact with air it evaporates, and the total pressure is then partially due to water vapour and partially due to air. Thus air in contact with water at 40° C. can contain about 7·2 per cent. of its volume of water vapour, and no more.

Oceans, seas, rivers and all moist or wet surfaces are always striving to saturate the air in contact with them with water vapour, the atmosphere absorbing as much as the temperature will allow. The water vapour molecules do not combine with the air molecules, they merely mix with them. If the atmosphere were still, the water vapour would diffuse into it and slowly spread upwards, and in time the whole atmosphere would become saturated. However, as the air becomes cooler with increasing elevation, the moisture content decreases as shown in Table II. Such calm conditions seldom exist, however, with the result that much of the atmosphere is unsaturated, and the air remains clear. Winds generally blow away the air in contact with water surfaces before saturation has involved any considerable thickness, and fresh unsaturated air replaces it. It thus comes about that, generally speaking, the lower atmosphere is unsaturated, and when clouds form by the condensation of water vapour it is because atmospheric movements have raised masses of moist air so high that cooling and condensation result.

When the water is much warmer than the air, a thin layer near the water surface is warmed and saturated with water vapour. Such warm air rises, mixes with the colder air and a mist is the result. On calm, clear nights, the damp air near the earth's surface becomes chilled, and the vapour condenses as fog. This is especially the case over low land in the valleys. At sea, warm damp air drifting over much colder water causes fog on cloudless nights or even during the day. However, fortunately the air is generally in motion and mist and fog are infrequent in most places. It is not until a height of some hundreds or thousands of feet is reached that the air is sufficiently cooled to produce cloud. As a rule the height at which condensation first takes place is clearly shown by the flat undersides of the clouds. All air rising above this level throws down vapour and forms cloud, whilst compensating down currents, even if cloudy, become clear. In a cloud of this kind rising currents are checked. The air contracts as some of the lighter water vapour becomes liquid. The water particles are so small that they remain suspended in the air and add to its density, and were it not for the sun shining on the upper side of the cloud and warming it, cumulus clouds would not rise in quite such magnificent globular masses as they often do. Cumulus clouds are essentially condensation and evaporation clouds. Many such clouds as they rise so increase their speed that they overshoot themselves.

Whilst they are rising, the globular snow-white masses have clearly defined outlines and rain often falls. However, the upward rush soon comes to an end, and being chilled by expansion the cloud begins to fall and disappear. As it does this it loses its sharp clear outlines and finally appears as a ghostly veil of its former self. No doubt its rapid disappearance is due partly to the rain or hail thrown down during its uprise. The phenomenon is well seen in thunderstorms.

The causes of the appearance and disappearance of cloud are of great interest, and as the physical changes involved are much the same as will have to be considered in other problems that require discussion, they deserve careful consideration here.

Much has been written about clouds and the various forms they exhibit ; but though they are of great interest, cloud forms do not throw much light upon the principles which underlie meteorological phenomena. However, they illustrate in a very interesting manner the phenomena produced when air is near the saturation point and air currents of different temperatures flow over one another.

It is a common occurrence, as we shall see later, for air currents from different sources, having greatly different temperatures and humidities, to co-exist at different heights in the troposphere, and their surfaces of contact frequently show light fleecy clouds which change their forms with great rapidity. In other cases, where the winds are converging, and the air is rising, condensation takes place, very thick masses of cloud are formed, and rain, snow or hail falls.

Four primary types of clouds can be recognised—cirrus, cumulus, stratus and nimbus. Intermediate secondary types are indicated by combining the names of the primary forms. These cloud forms have the following characteristics :—

(1) *Cirrus* (Ci.). Detached white clouds of delicate hair- or thread-like structure, commonly known as " horse tails," situated high up in the atmosphere. Occasionally they are arranged in parallel bands, which, owing to perspective, appear to converge as they approach the horizon.

(2) *Cirro-stratus* (Ci.-St.). Little detail is shown by this form, the clouds being whitish sheets which often cover the whole sky.

(3) *Cirro-cumulus* (Ci.-Cu.). " Mackerel " sky. Small globular masses, or delicate white flakes, arranged in groups and often in lines.

(4) *Alto-stratus* (A.-St.). A thick or somewhat thin sheet of a grey or bluish colour, sometimes in compact masses of dark grey colour, generally resting at levels much lower than cirrus cloud forms. Sometimes the sun or moon may be dimly seen through them.

(5) *Alto-cumulus* (A.-Cu.). Somewhat densely packed large globular masses or rolls of cloud.

(6) *Strato-cumulus* (St.-Cu.). Large lumpy masses or rolls of cloud, sometimes separated from each other by blue sky, especially in winter.

(7) *Nimbus* (Nb.). A thick layer of dark cloud with ragged edges, the details of which become less and less distinct the heavier the rain or snow fall.

(8) *Cumulus* (Cu.). A thick cloud of which the upper surface is dome-shaped. The base is horizontal.

(9) *Cumulo-nimbus* (Cu.-Nb.). Shower or thunder cloud.

(10) *Stratus* (St.). A low-lying uniform layer of cloud.

Much discussion has taken place concerning the causes of some of these cloud forms. Their appearances are of course due to the lighting effects resulting from the angle at which the sun's rays strike them. It is a common saying that there is "a silver lining to every cloud," and when the cloud is thin it is all "silver lining." The beauty of the various cloud forms arises from the contrast between the dark clouds, the white silvery water drops on their sunlit sides and the blue sky. Sometimes this "silver lining" becomes a brilliant red, and this in turn makes the adjacent blue sky appear a blue-green.

Helmholtz suggested that the ridged appearance of some clouds is due to the formation of waves between strata of air at different temperatures, densities and humidities, the clouds formed being broken-up by these waves. However, the small cloud masses and rolls often show vortex motions, probably due to direct heating from the sun or the ground ; for many of these small clouds develop their characteristic features rapidly and then evaporate and disappear. The "horse tails" of cirrus clouds, often seen in the front of approaching cyclones, appear to be due to the tearing up of small clouds which form from air where discontinuities exist, *i.e.* where layers of air having different temperatures and humidities, and different velocities, are in contact.

We are mainly interested here in the properties of gases and vapours, but it is useful to consider the phenomena presented by matter in its three states. Maxwell defined the difference between the properties of solids, liquids and

gases. He regarded a "solid" as a body which when pressed gently in one direction does not expand continuously at right-angles to the pressure. Thus a column of solid material supporting a building does not get shorter and shorter under the load to which it is subjected. It may be elastic and take an elastic set when first loaded, but afterwards it always has the same length at the same temperature. However, a solid will only carry a certain load. If overloaded it will give way, either by fracture or plastic flow. When a substance is unable to retain its shape under load, however small the load may be, it is called a "liquid." Pitch, for example, is a brittle hard substance, but a column of it will not even carry its own weight without shortening and spreading out slowly and continuously. Indeed a column of pitch will shorten and spread out slowly to form a disc. Glacier ice in bulk is also a liquid, and runs slowly down valleys in the form of huge rivers, although it is hard and brittle. On the other hand hills made of clay are quite stable, if not subjected to vibration or much wetted by rain, and this in spite of the fact that clay has a much lower tensile strength than ice.

There are two main classes of fluids. If we put a small quantity of a fluid of the first class, say water, into a vessel, it will only partially fill it, the rest of the space being occupied by its vapour or some other fluid. Its volume remains constant at the same temperature as long as the vapour is unable to escape, for then evaporation and condensation are equal in amount. Fluids having this property of occupying a restricted space and forming a free surface, and of obeying the dictates of gravity freely, are called "liquids." Water is a liquid. If on the contrary, the fluid we put in the closed vessel be a gas, one of the second class of fluids, then, however small a portion we introduce, it will expand and fill the vessel, or at least as much of the vessel as is not occupied by its liquid form. Fluids having this property of unlimited expansion if not kept in restraint are called "gases." It has already been explained that it is the force of gravity that holds the atmosphere on the earth and accounts for its decreasing pressure with increasing distance from the earth's surface. The atmosphere does not, like water, remain as a mass resting in hollows ; nor has it a dense upper free surface like that of the sea.

All bodies, whether solid, liquid or gaseous, consist of small bodies called *atoms*, most of which can combine with each other to form *molecules*. At one time the elements were regarded as being the ultimate particles of matter ;

but it is now known that they are extremely stable compounds formed of extremely minute particles. All the gases of the atmosphere given in Table I, except carbon dioxide, are pure elements, as also are aluminium, gold, silver, copper, carbon, etc. Indeed all matter, be it solid, liquid or gaseous, consists of combinations of the 92 known elements. A few of these elements are found in a comparatively pure state in Nature, but the majority of them are chemically combined with each other to form such substances as water, table salt, sugar, wood, bricks, etc. Chemists have succeeded in breaking up such compound substances and separating the elements which form them the one from the other. This is effected by heat or by electrical means, and when the elements have been separated, or obtained as simple compounds, they may be stored in suitable receptacles, and can be mixed and caused to unite to form particular substances required. Thus, in a gas burner, the hydrogen forming a portion of the gas unites with the oxygen of the air to form water, with the production of flame. This water can be condensed upon a cold piece of iron placed above the burning jet.

In vegetation the carbonic acid gas of the air enters the leaves through pores in their undersides, and is there broken up by the agency of the sun's rays into carbon and oxygen, the carbon being deposited in the solid form to make wood, bark, leaves, etc., and the oxygen gas rejected. Indeed by far the greater part of a tree comes really from the air, the root merely providing water and fertilisers. When wood is heated and the gases driven off, charcoal (carbon) remains, and all this carbon has been obtained from the carbonic acid gas in the air, not from the ground.

It is a remarkable circumstance that the leaves of a tree can break up carbonic acid, and make use of the carbon, but cannot separate water vapour from the air. The plant obtains its water from the moist ground into which its roots grow, or from mist in the saturated air such as exists in dense gloomy forests.

It has been found that water consists of two atoms of hydrogen and one atom of oxygen chemically combined. Carbonic acid gas consists of two atoms of oxygen and one atom of carbon. Chemists, for convenience, write O for oxygen, H for hydrogen, C for carbon, Cu for copper, etc. When two or more atoms are combined to form a compound, such as water, they write (for water) H_2O, or for carbonic acid gas CO_2. Oxygen, as it exists in the atmosphere,

consists of two atoms of oxygen in combination. Such a combination, whether of the same or different elements, is known as a "molecule." Atmospheric oxygen is therefore a molecule consisting of two oxygen atoms and is written O_2. Nitrogen is also a molecule written N_2. Argon, neon, krypton, helium and xenon, however, exist in the atmosphere as free atoms, not as molecules, and helium in the gaseous state is written He.

Suppose we have a hollow cubical vessel containing 64 molecules of a gas, and assume that these are separated by equal distances, and are at a pressure of 10 lbs. per square inch, a cross-section of the vessel being as shown in Fig. 37. Here each molecule dominates one sixty-fourth part of the space. Now if we reduce the cubical contents of the vessel

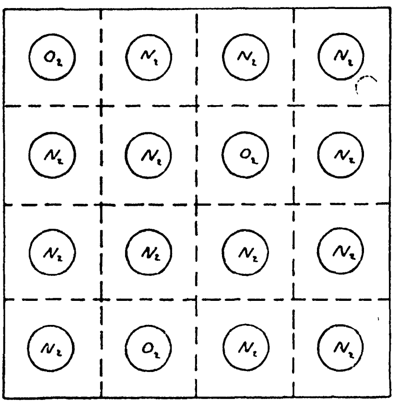


Fig. 37.

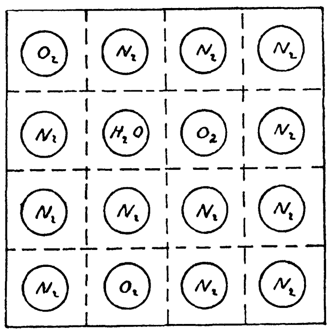


Fig. 38.

to one-half, the molecules are pressed closer together, the pressure rises to 20 lbs. per square inch, and the result is as shown in Fig. 38. In the gaseous state it is convenient to regard all kinds of molecules as being of the same size, or rather as dominating similar volumes at similar temperatures and pressures. This extremely important generalisation known as *Avogadro's Law* is worded as follows:—All gases (at the same temperature and pressure) consist, within equal volumes, of equal numbers of molecules or atoms. This is a general law for all gases, and Figs. 37 and 38 illustrate it. We see, therefore, that under the same conditions of temperature and pressure equal volumes of all gases contain equal numbers of molecules or atoms, and that the weight of the gas is the sum of the weights of all the molecules or atoms.

It must be remembered that the molecules in a gas are

not at rest. They are moving about, some at very high velocities and others much more slowly. Nor are all the molecules as regularly distributed as the diagrams show, where we are really considering average conditions of distribution not individual ones. But the molecules are so numerous that the average condition gives quite a satisfactory indication of the facts. When a gas is near its condensation temperature, however, heavier molecules form.

We have seen that all bodies, whether solid, liquid or gaseous, consist of a number of small parts called atoms and molecules. The molecule is built up of two or more atoms and is stable under many conditions. It may, however, be broken up by heat or by coming into contact with other molecules or atoms for which one of its constituents has a greater affinity. Hydrogen and oxygen gases may be mixed at ordinary temperatures without changing either substance, but if the mixture be considerably heated, the molecules of the two gases are broken up and the free (nascent) atoms then combine with evolution of heat to form water, H_2O.

Atoms in most cases can be broken up only by collision with certain other bodies. However the atoms of some elements are breaking up of their own accord, and in this automatic disruptive process they radiate various rays, and throw off what are called "emanations." The remaining matter then either undergoes further disruption, or else stabilises itself as one or more of the other known elements (*e.g.* lead).

In all bodies the atoms and molecules are in a great state of agitation. The hotter the body the more violently its parts are agitated, and the more room they require. In fluids there is no restriction to the excursions of a molecule or atom. The particles can only as a rule travel very small distances before encountering other particles, and after such encounters they fly off in other directions. Hence, in fluids, the path of a molecule or atom is not confined within a limited area, as is the case to a large extent with solids, but may penetrate to any part of the space occupied by the fluid. We conclude that the expansive force of a gas when heated is due to the high velocity attained by the particles which compose the gas, the particles bombarding each other and the walls of the containing vessel. A stone thrown upwards soon comes to rest and then falls to earth. The atoms and molecules of a gas when they fly upwards are also reduced in velocity by the action of gravity. On this account they are subject to an excess downward

pull, and they cannot, to any considerable extent, escape into space, even when they are at the upper limits of the atmosphere. Exactly what takes place there, however, is not known.

A mass of gas, unlike a solid, cannot be said to have any particular volume corresponding to any particular temperature, for omitting gravitational and other restrictive forces, it is capable of expanding so as to occupy any space however large. Even extra-planetary space is not free from matter, about one atom or molecule existing in every cubic inch. The larger the enclosed space occupied by the gas and the fewer the number of particles occupying it, the lower is the pressure on the boundary walls containing the gas.

Since the hotter a body is, the more violently its atoms and molecules are agitated, it is seen that both temperature and pressure depend upon the energy of the moving particles. This conception requires extension, however; for, as we have seen, all the particles are not moving with equal velocities. We must adopt a statistical view of the system, and distribute the molecules into groups, according to the velocities with which at a given instant they happen to be moving. It appears then, that of the molecules composing the volume considered, some are moving very slowly, a few are moving with enormous velocities, and the greater number with intermediate velocities. To compare one system, or volume of gas, with another, we must take the mean of the squares of all the velocities, for we know, *e.g.*, that a motor car collision at 40 miles per hour is sixteen times as destructive as one at 10 miles per hour.

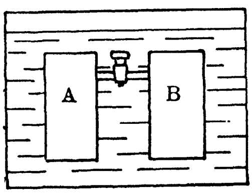


Fig. 39.—Isothermal Expansion Apparatus.

As the temperature of a gas is proportional to the mean of the squares of all the velocities, it might be supposed that when a gas expands, its temperature would not change, and it is true that when a gas expands without forcing outwards the walls that bound it, its temperature does not vary appreciably.

Air may expand either isothermally or adiabatically. *Isothermal expansion* can be effected in several ways. The most simple is to use an apparatus made as shown in Fig. 39. Here two vessels connected by a pipe and stopcock are immersed in a receptacle containing water the temperature of which is indicated by a thermometer. The vessel *A*

contains compressed air, whilst *B* is vacuous. By means of a stirrer the water is caused to circulate rapidly so as to keep the fluid always at the same temperature throughout. When the stopcock is opened, the air in *A* expands and cools, but as it rushes into *B* it is compressed again and warms, the heat energy gained by *B* being nearly equal to that lost by *A*, the temperature of the water jacket being seen by the thermometer to be unaltered. Here, if the two vessels are of equal size, the volume of the air has doubled without appreciable ultimate change of temperature.

Free expansion through a porous plug illustrates isothermal expansion in another way. When air under pressure is forced through a porous plug it issues almost exactly at the temperature it had when it entered the plug, but at a much lower pressure. In passing through the pores of the plug friction is set up between one portion of the air and another, and between the air and the walls of the pores. The heat thus produced is about equal to that lost by the expanding gas, and the temperature does not change appreciably.

When air saturated with water vapour rises in the atmosphere it does work by displacing the surrounding air and increasing its own volume. On account of this volume increase it could hold more water than before ; but the temperature falls so considerably during expansion that the dewpoint is reached and moisture is precipitated as cloud. Conversely, when moist air passes from high to low levels, although the volume is decreased, and on this account the air will hold less moisture, the temperature is raised so greatly that the air can hold more moisture. If the compression had taken place at constant temperature the air would have become more saturated and mist or cloud formed.

In the atmosphere, when a mass of air rises, as it rises it drives away the surrounding air. It thus does work, and heat is required to enable it to do the work, and so we find that the temperature of the expanding gas falls. On the other hand, when a mass of air descends in the atmosphere it contracts in volume and work is done upon it, its temperature rising.

It has already been stated that the foregoing is why the temperature falls as air rises, and also why the temperature rises as the air falls. It results from the slowness of the conduction of heat in air from one level to another as compared with the rapidity with which large masses of air are carried from one height to another by vertical movements. If a vertical column of the atmosphere were left to itself,

until, by conduction of heat, it had attained a condition of thermal equilibrium, the temperature would be the same throughout; or, in other words, gravity produces no effect in the dense bottom of the column to make it hotter or colder than the rarefied top. This result is, however, by no means applicable to our atmosphere, for the irregularity of the sun's distribution of heat into it, the freedom with which it can radiate into space, and the vertical rise and fall of masses of the air, result in a temperature distribution which is of quite a different kind.

To calculate the exact changes of temperature the air undergoes as it is raised and lowered by currents is a difficult and complicated matter, and need not be attempted here, for it will in some measure be considered in a later chapter. The main reason for this complication is that the atmosphere contains water vapour. As the temperature falls, if the air is saturated, some vapour condenses and forms cloud or fog. Heat is liberated by this change from vapour to moisture, and the rapidity of the fall of temperature is checked while condensation is taking place. If the temperature should fall below the freezing-point, and rain drops freeze, heat is again liberated. Sometimes water vapour turns directly into ice and forms snow, etc., and a considerable amount of heat is then liberated.

All changes of temperature in gases, liquids and solids, due to contact with hot or cold bodies, take place somewhat slowly. If a bar of metal be heated at one end the heat travels slowly along the bar, more slowly in the case of iron than gold. Gases absorb different radiations. Thus ozone, oxygen and carbonic acid gas, are much more opaque to the sun's heat rays than is nitrogen ; and again their latent heats are not the same.

The meaning of *latent heat* requires some explanation. The practical unit of heat is the amount of heat required to raise one pound of water one degree Fahrenheit in temperature. When water is boiled, to convert the liquid into steam or vapour a good deal of heat is required. Suppose that the temperature of the water is 60° F. when the vessel containing it is put on the fire, and that the vessel contains one pound of water. When the temperature reaches the boiling-point, 212° F., the temperature has been raised 152° F., and about 152 units of heat have been passed into the water. It then begins to boil ; but it does not continue to rise in temperature, nor does it all turn into vapour at once, for heat must be supplied for some time to convert it wholly into steam. It has been ascertained that to boil

one pound of water at 212° F. requires as much heat as would raise one pound of water 965° F. in temperature. Now steam is water vapour, and when it condenses it gives out the great amount of energy stored up as latent heat. A similar phenomenon is experienced when ice is melted. The temperature of water in which there is melting ice does not change until all the ice has disappeared. In this case about 110 practical units of heat are required to turn the ice into water. It thus appears that heat is given out by water vapour without change of temperature in considerable quantity when it condenses or freezes. The effect of this latent heat on the temperature changes which would result from change of height when the air rises or falls is felt appreciably only in the lower portion of the troposphere, where there is much water vapour, and although latent heat must be taken note of when considering the physics of the lower four miles of the atmosphere, the effect is not of much importance at higher levels.

When water is separated out as cloud or fog, by the condensation of the vapour in the air, the droplets formed do not necessarily fall down to the earth quickly. They may remain as a cloud of fine water particles which practically float ; but they increase the density of the mass of air in which they exist. However, when the particles grow sufficiently large or heavy, they do fall in the form of rain, hail or snow.

Air which is quite free from dust and electrified particles called " ions " may be cooled much below the temperature at which condensation should take place without forming cloud. This is due to the fact that for condensation the presence of some solid nucleus or particle is required to initiate the precipitation. Clean water in a clean flask boils by " bumping." The water becomes superheated and the vapour is given off as gulps of steam. But if a thin piece of tin be dropped into the water, continuous streams of small bubbles shoot out from the points and edges of the metal and the " bumping " ceases. The large number of dust particles in the air has already been pointed out. It is upon these dust particles and upon " ions " that the vapour condenses and forms droplets, the greater the number of particles there are present the greater the number and the smaller the water particles formed. Thus in a fog the drops are very small in diameter and they fall very slowly indeed. In heavy rain the drops are nearly one hundred and fifty times larger in diameter and they fall seventeen hundred times as fast.

In Table VII some figures illustrative of this are given.

TABLE VII.

Fog, Mist and Rain Data.

Description.	Diam. of Drops, inches.	Velocity of Fall, miles per hour.	Height of Origin, feet.
Fog	0·0004	0·0067	0
Mist	0·004	0·56	330
Drizzle	0·005	1·68	660
Light rain	0·016	4·47	1,960
Moderate rain	0·040	8·94	1,960
Heavy rain	0·060	11·17	3,300
Thunder rain	0·084	13·41	4,000

It will be noticed that the points of origin of the rain drops are higher the larger the drops, and that the large and heavy drops fall very much more rapidly than the light ones. This dependence of the average size of the drop on the height of origin is no doubt due to the fewer condensation nuclei at great heights. The point of origin of large drops in thunderstorms is often at much greater heights even than the table shows. Indeed, in thunder rain the drops grow so large that as they fall quickly through the air they are broken up and thereby become electrically charged; and the high-tension electricity thus produced is regarded as giving rise to lightning.

The lower rain clouds are at a height of about 2,500 feet as a rule; but this figure may be considerably greater or less. Cumulus clouds generally have their bases 5,000 feet high. When there are clouds below 1,000 feet they may exist as "scud." They are generally seen just before rain falls, drifting along at low levels. When rain is actually falling heavily the drops so obscure the view of the clouds that little if any detail is to be seen.

As has already been mentioned, cloud is also thrown down to a small extent where air currents of different humidity and temperature rest upon each other. At their point of contact waves are formed similar to those between water and oil resting upon it, and the cloud is formed in hazy streaks running parallel with the waves. Indeed, as previously stated, cloud effects are often of great beauty and interest, especially when they are illuminated by the rays of the low altitude sun in the morning and evening.

For the purpose of determining the pressure of the aqueous vapour in the atmosphere the dewpoint temperature is determined. This is the temperature to which the atmosphere must be brought at any time for the air to become saturated with water vapour. The reading can be made in several ways. However, the most common and most reliable method is by reading the temperatures shown by dry- and wet-bulb thermometers.

The rate at which evaporation takes place from a wet wick or liquid water surface depends upon the humidity of the surrounding air ; the drier the air the greater the evaporation, and the greater the rate of evaporation the lower the temperature the wick assumes. The dry- and wet-bulb instrument consists of two ordinary thermometers. Round the bulb of one is tied a small piece of muslin, and from the muslin hangs a wick extending down into a vessel of water ; up this wick the water is raised by capillary forces, and the muslin is kept wet ; the evaporation from the surface of the muslin cools the bulb of this thermometer, and the two thermometers then indicate different temperatures. The less the moisture present in the air, the greater the evaporation from the muslin surface, and therefore the bigger the difference of temperature between the thermometers. To obtain the dewpoint temperature Glaisher's tables are usually consulted.

Example :—

Dry-bulb temperature . . .	53° F.
Wet-bulb temperature . . .	49° F.
Difference	4° F.

For the factor corresponding to 53° Glaisher gives the figure 2. Then $4° \times 2 = 8°$. Subtracting this from 53° we get 45°, which is the dewpoint.

There are many other means of ascertaining the dewpoint. For a description of them a work on practical Meteorology should be consulted.

CHAPTER VI.

AIR DENSITY AND WATER VAPOUR.

It has already been pointed out that if the atmosphere did not receive, or allow to pass from it into space, any radiations carrying energy, it would slowly assume an even temperature throughout, provided that the earth's surface temperature, due to internal heat, did not vary from place to place ; and this would be the case in spite of the differences of pressure with height. In these circumstances the density conditions of the atmosphere would be entirely due to gravity and temperature. The latter would be the same everywhere, and consequently there would be no air movements or, as we call them, winds. On the earth's surface the pressure would vary only by about five and a half millibars between the equator and the poles ; this difference would not result in air movements, nor would air movements result from the presence of water, or from the rotation of the earth. The sun and moon are supposed to be non-existent, and, therefore, there would be no tidal movements.

It has not been considered advisable to notice theories, purporting to explain air movements, which do not seem to be justifiable ; but an exception must be made in the case of one which has received a good deal of support. This is the " heaping up " theory framed to account for the existence of the two belts of high pressure in latitudes 30° to 35° north and south of the equator—the " horse latitudes." These high-pressure belts are said to be due to the centrifugal force due to the rotation of the earth. However, seeing that this force affects the solid earth and the liquid oceans, as well as the atmosphere, and that it is the cause of the earth's oblateness, it is not clear how it could affect atmospheric pressures in such a way. But even if it did heap up the air, the high-pressure belts formed in this way would be of a permanent character, and like the pressure increase due to gravity at the poles would not result in air movements at all, nor would they vary with the seasons.

The primary cause of the winds must be temperature differences, causing density and pressure differences. However, owing to the revolution of our globe, and its rapid

movement in its orbit, if any material particles did reach the earth from space, especially in low latitudes, as they would not partake of the angular momentum of the atmosphere they would by collision with the air impart movements to it with respect to the earth, movements which would be recognised as easterly winds. These would, of course, be primarily in the upper atmosphere, but they might affect lower levels by viscous drag. This possible cause of wind will be considered in a subsequent chapter. For the present only those winds resulting from differences of density, due to differences of temperature, and the rotation of the earth, will be dealt with.

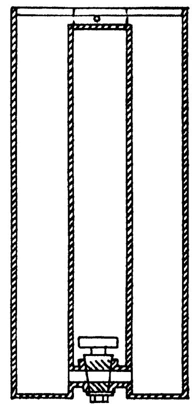


Fig. 40.—Apparatus for Determining Temperature of Maximum Density of Water.

Of course much depends upon the varying warming effect of the sun's heat and light rays in different latitudes, and over sea and land, and also upon the extent to which the atmosphere intercepts radiations at different levels. The much more difficult question of the effect of material particles ejected into space by the sun, and caught by our atmosphere in high latitudes, cannot, however, be ignored. Indeed, at this juncture it must be stated that we must be prepared to accept as reasonable the idea that the sun may greatly affect the earth's temperature in this indirect way, and therefore densities, and so be a potent influence in the flow of the winds.

The effect of differences of density in producing motion in a fluid can be shown by the method of ascertaining the temperature of maximum density of water. For this latter purpose Joule employed a vessel, indicated in Fig. 40, consisting of two vertical cylinders each four and a half feet in height and six inches in diameter, connected below by a wide tube and stopcock, and above by a trough. The whole was filled with water up to such a level that it filled the top channel and flowed freely through it. In this channel was placed a glass gravity bead which just floated. The very smallest differences of density between the two portions of water in the two columns were sufficient to produce a current and to move the bead in the channel when the stopcock was opened.

The cock in the connecting tube being closed, the temperature of the water in the two cylinders was adjusted by the addition of cold or hot water, the water being well

mixed by stirring ; when the water had come to rest, the temperature of each column was accurately measured, and the cock then opened. If a current was observed in the channel, it indicated that the water in the cylinder towards which the current flowed was the heavier or denser. Now it was known that water has a maximum density at about 40° F. By finding a pair of temperatures, one above 40° F. and the other below 40° F., at which there was no flow in the trough, the densities in the two cylinders thus being equal, and by obtaining a series of such temperature pairs, the point of maximum density was found to be 39·1° F.

When a pond is cooled on a frosty night, the cold surface water descends, and warmer water rises to take its place. However, after the surface temperature has reached 39·1° F., this sinking of the cold water ceases to take place, and the surface water gradually falls to the freezing-point. In

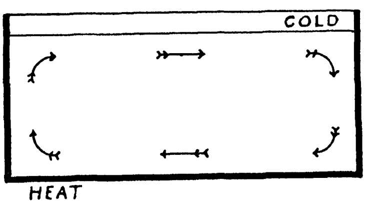


Fig. 41.

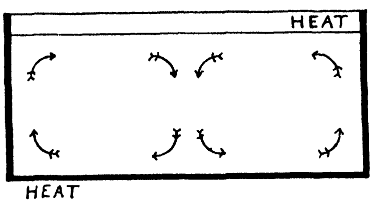


Fig. 42.

Figs. 41, 42.—Circulation of Water in Differently Heated Tanks.

these circumstances the water at the bottom of the pond may have a temperature of nearly 40° F., whilst the ice on the surface is below 32° F.

If it were not that the point of greatest density of water is well above the freezing-point, ponds and lakes would first freeze at the bottom, and the ice would thicken until the whole of the water changed to ice.

If a trough nearly full of water, its temperature being well above that of the maximum density, be heated at the bottom at one end, and cooled at the top at the other end (see Fig. 41), the warmed water will rise vertically to the upper surface and flow towards the cool end, whilst cold water will sink and flow along the bottom towards the warm end. We here see that when two masses of water at different temperatures are placed side by side, currents are set up, and the warm, light water places itself above the cold, heavy water. In such circumstances the water cannot circulate in directions other than those the arrows indicate. In Fig. 42 the water is heated at the bottom at one end of the trough and also at the top at the other end of the trough.

The direction of circulation is then as shown by the arrows. Thus we have two distinct systems of circulation, such as occur in the troposphere, one (Fig. 42) between the " horse latitudes " and the equator, and the other (Fig. 41) between the " horse latitudes " and the poles.

This phenomenon of flow in obedience to density differences is made use of in many motor-cars for the purpose of keeping the engine cylinders cool. The heated water in the jackets surrounding the cylinders rises and flows into the top of the radiator, and, as it flows downwards there, it is cooled by the air current passing through the radiator, then flowing through a pipe into the bottom of the cylinder jackets. The difference between the condition of the water of the radiator column and the cylinder jacket column, as regards density, is thus maintained, and the current of

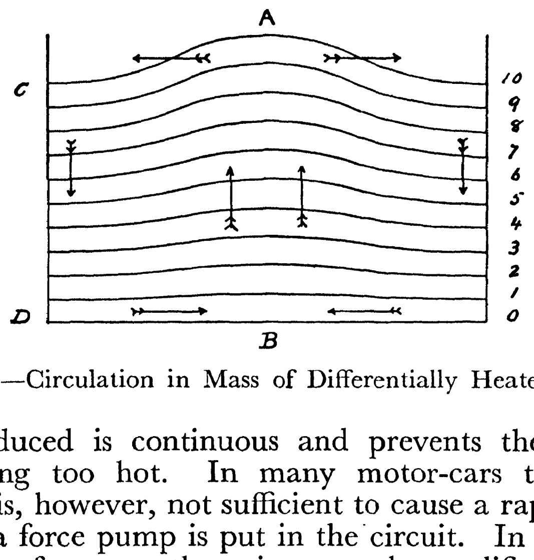


Fig. 43.—Circulation in Mass of Differentially Heated Air.

water produced is continuous and prevents the cylinders from getting too hot. In many motor-cars the density difference is, however, not sufficient to cause a rapid enough flow, and a force pump is put in the circuit. In the case of the winds, of course, there is no such amplifier at work, and the flow must be entirely due to differences of density, resulting from variations of temperature.

The manner in which air currents would be produced in a differentially heated mass of air is shown in Fig. 43. The horizontal lines are isotherms (lines of equal temperature, which are here drawn to an arbitrary scale), the top lines being the warmest. The vertical column of air at *A B* has been warmed by equal increments between each isotherm throughout its height. On each side the heating has been less and less as the containing sides are approached. At the margins the isotherms are quite horizontal. Owing to its higher temperature the central portion, however, rises

in the form of a dome above the surrounding cooler air. The mass, however, cannot rest in this condition, and the air flows in the direction of the arrows until the isotherms become equally spaced. Whilst this adjustment is taking place there are low pressures on the ground over the central portion, and circular isobars will develop there.

In the atmosphere, however, the adjustment of pressures would not take place by such direct movements as the arrows show in Figs. 42 and 43, for the air would circulate spirally round the centre of low pressure, as it does in cyclones. This movement would continue until destroyed by the viscous friction of the air and the disappearance of temperature differences.

Another effect of such atmospheric movements is to produce changes of temperature in the air owing to adiabatic expansion and compression when changes of level take place.

Before attempting to deal further with this matter the laws governing the expansion and contraction of gases, and other matters, must be considered in more detail.

Although the agitation of the molecules and atoms forming the atmosphere has already received some consideration, there remain some features of atmospheric motion which are of interest and which may be referred to here.

When a mass of air moves from point to point we regard it as a wind. Now such movements in a mass of air like the earth's atmosphere must be in the nature of re-entrant currents. For example, for every south wind there must be a compensating north wind. This is due to the fact that each small stream of air as it moves must be replaced in its rear by fresh air, and must push out of its way air in front of it. It is necessary, therefore, to regard air movements from a detached point of view, and endeavour to see all the phenomena at all portions of the re-entrant currents. Local disturbances exist in the form of whirls, such as dust whirls, gusts of wind, tornadoes in the tropics, or horizontal rolling movements often seen in thunderstorms. Large manifestations of such whirls take the form of cyclones and anticyclones, in which the re-entrant currents form great spirals with approximately vertical axes of rotation. Indeed the great atmospheric movements which we recognise as the dominant winds are of this nature. The South Polar Cyclone (see Fig. 59) is perhaps the most impressive form of re-entrant current on the earth. The trade winds, however, which blow on each side of the "doldrums" as far as the "horse latitudes," also circulate round the globe in great whirls.

Although the conditions which would result from the local heating of a mass of air as illustrated in Fig. 43 are correct, the arrangement of the isotherms in the atmosphere is not so simple as we might on first thought expect it to be. This is due to the fact that the tropopause is the point where the temperature is lowest, its position being the result of heat rising from low levels meeting the heat energy descending from high levels. Isotherms are also displaced by air movements set up by local differences of density.

Movements of masses of air still constitute winds even when the masses are of great tenuity, as at high levels in the stratosphere. In the automatic vacuum brake apparatus installed on most of our British railway trains, the vacuum required is obtained by means of a steam jet

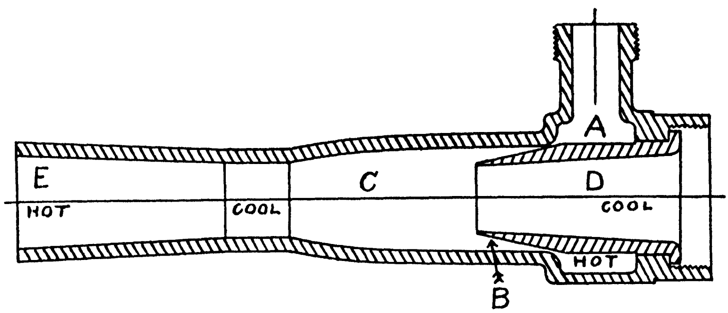


Fig. 44.—Vacuum Brake Ejector.

which blows the air out of the pipes and cylinders. The instrument used for this purpose is called an ejector, and one form of it is illustrated in Fig. 44. High-pressure steam is admitted to the annular chamber *A*, and escapes through the annular flared nozzle *B*. As the steam leaves the constricted opening of the nozzle it expands both laterally and longitudinally, and by the time it has reached the chamber *C* it has expanded and cooled so much that its pressure is far below that of the atmosphere, and what may be described as a " vacuum of translation " is set up. Into this steam the air from the pipe *D* rushes, and when the mixture reaches the cone *E* it piles itself up against the pressure of the atmosphere, at the pressure of which it escapes. The annular steam chamber *A*, when the instrument is working, is so hot that it is impossible to touch it without being burned. However, in the chamber *C* both the steam and the air have expanded adiabatically and become so cooled that *C* can be grasped by the hand with comfort. At

the end of the cone E compression has reheated the mixed air and steam, and the delivery pipe is too hot to touch.

We can compare the temperature conditions of air moving vertically in the troposphere with those in the ejector. For example, a mass of rising air expands and cools, just as does the steam after leaving the chamber A ; whilst in the case of a descending mass of air it is compressed and heated as it piles up against the lower atmosphere, as in the cone E.

The illustrations generally given of the effect of differences of density in causing movements in a fluid, *i.e.* noting what takes place when water and air are irregularly heated, are sound in themselves ; but it must be remembered that

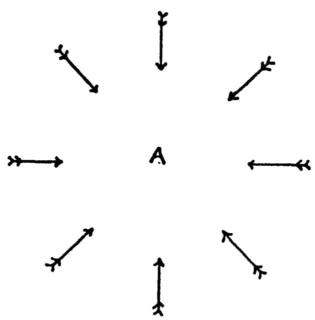


Fig. 45.—Initial Movement of Air at Earth's Surface in Cyclone.

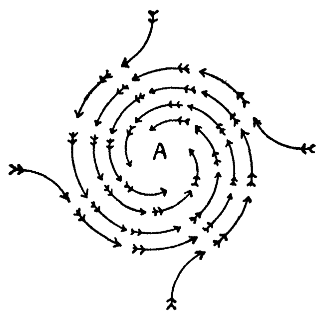


Fig. 46.—Direction of Circulation at Earth's Surface in Northern Hemisphere Cyclone.

small masses of air when heated do not expand quite as does the atmosphere considered as a whole.

In the case of water, when it is heated from below, currents are produced, and when these have died down the liquid is warmer at the top than at the bottom. In the case of the atmosphere, when it is heated from below, currents of air are produced and when they have died down the fluid is still colder at the top than at the bottom. It has been explained that this is due to the expansion of the air as it rises to considerable heights. The short-distance change of level movements of small masses of air, such as we notice near the earth's surface, change the temperatures of these masses only very slightly.

Although the isotherms are not arranged in Fig. 43 as they are in the atmosphere, we will regard the illustration as a section across a cyclone, and consider that the air circulation to and from the centre is as shown by the arrows.

In the Northern Hemisphere a mass of air as it moves

towards the north finds itself over ground which is moving less rapidly to the east than itself and, as regards the earth's surface, tends to swerve to the right. But this movement due to the rotation of the earth sets up air pressure conditions which prevent the mass of air from changing its velocity, and the air is caused to swerve to the right.

Now it does not matter from which point of the compass the winds blow ; in the Northern Hemisphere they are always deflected to the right, and in the Southern Hemisphere to the left, by the rotation of the earth. On this account they do not move directly towards the centre of the cyclone,

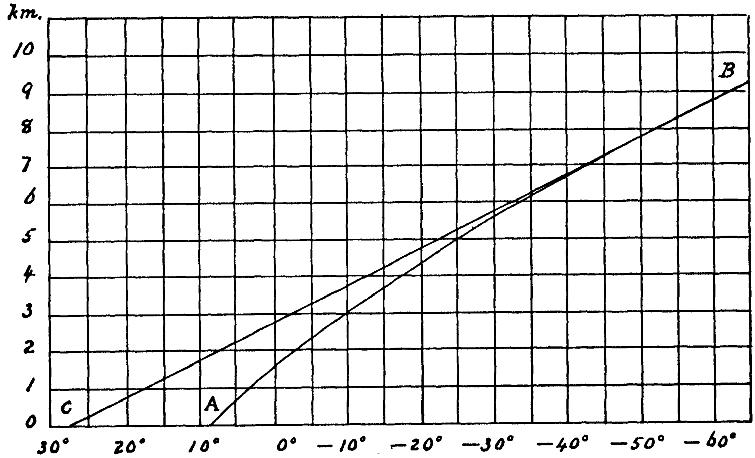


Fig. 47.—Illustrating Convective Circulation of Dry and Saturated Air.

as in Fig. 45, but are deflected as in Fig. 46 and move spirally towards the centre. Here the winds denoted by the arrows are striving to turn to the right, but the low-pressure area they thus form compels them to turn to the left instead.

As the air bunches together in its movement towards the centre *A*, it rises, and at a certain height flows outwards, then sinking down again as shown in Fig. 43. Now the behaviour of dry air as it rises and falls differs from that of air saturated with water vapour, owing to the fact that in the latter case the vapour condenses as the air rises, forms cloud and liberates heat, this heat checking the fall of temperature.

For example, a mass of saturated air at 9° C. as it rises falls in temperature at the rate shown by the curve *A B* of Fig. 47, until at a height of about 9 km. it has a temperature only a little over −62° C. This mass of dry air, for it has now lost nearly all its moisture, brought down again from

B to *C*, has a temperature at the earth's surface of about 27° C., about 18° above the temperature it had at *A*. Further reference will be made to this in a later chapter.

We have seen that on an average the earth's surface receives only about 24 per cent. of the sun's heat rays, the rest being intercepted by the atmosphere. Most of the heat is arrested at heights of less than 3 kilometres. In this lower region of the troposphere changes of temperature with height are very irregular indeed. It would appear that, owing to this heating of the air by the sun, even at heights above 3 km. the temperature gradient is such that there is very little tendency for vertical convection currents to be set up of sufficient strength to cause thunderstorms. However, at heights well below 3 km. the temperature gradient is such that there is often a powerful inducement for hot saturated air to ascend rapidly to considerable heights, and when this occurs condensation takes place so rapidly that we have heavy rain, hail, lightning and thunder.

Many hypotheses, which may seem plausible when applied to cyclones a few hundreds of miles in diameter, fail completely to account for the facts when applied to such great cyclones as are a regular feature in high latitudes. The matter will be further discussed when cyclones come to be treated in detail.

Over ice- and snow-covered areas winds are caused by the cooling of the air near the surface. Surface radiation in the clear air of high latitudes is very active, owing to the low altitude of the sun and the small quantity of water vapour in the air. In elevated areas like Greenland and the elevated Antarctic Continent, a comparatively thin layer of cold air forms when there are no strong winds to carry it away, and this air slides down the slopes to low levels. The tendency is to form local cold air streams down depressions in the surfaces, and these do not seem to produce pressure or wind effects which can properly be called anticyclonic except when the areas are very elevated. The most remarkable of such regions, as regards seasonal pressure and temperature changes, occur in the elevated plateaux of Asia, the heights of which reach more than twelve thousand feet above the sea. At such elevations there is little moisture, and the winter snow is largely melted off each year. These conditions favour high pressures during the winter and low pressures during the summer. The temperature gradients set up under such conditions are not properly speaking in the upper atmosphere as is the case in ordinary cyclones and anticyclones ; they are

almost entirely elevated ground phenomena. On the Asiatic plateaux the pressures have an annual range of over forty millibars. Indeed the difference between the temperature and pressure conditions of the Northern and Southern Hemispheres is due to the high lands of Asia, North America and Europe rather than to differences in the areas covered by low land and water. For example, India owes the rains of the monsoon to the effect of the low pressures of the plateaux beyond its northern borders on the pressures and winds of the tropical belt.

Gradients of pressure and temperature have been referred to without explanation, the expression "gradient" being to some extent in common use. When a road is steep it is said to have a steep "gradient." The word "gradient" means moving by steps, rising or descending. We speak of a gradient of "one in ten," *i.e.* a rise or fall of one foot in ten feet. The gradient of pressure may be expressed as so many millibars per mile, and temperature gradients as so many degrees per mile. Now as the winds pass at low angles across the isobars it is found that their strength shows a close relationship to the steepness of the gradient. On a chart of the weather, for example, the nearer the isobars are together the stronger are the winds.

In all scientific questions it is necessary to make sure that the forces called into play to produce certain effects are sufficiently powerful for the purpose. Such matters can only be settled by mathematical treatment, and although this has not been done here, care has been taken that such matters of proportion have had careful consideration.

Now the pressures the isobars indicate are due to the weights of the air columns above them, and calculation shows that the strength of the wind at any point is related to the distance apart of the isobars. Winds which are of such a strength as can be shown to be directly related to the distance apart of the isobars and the latitude are called "geostrophic winds," and nearly all winds have been shown to be of this kind. It is thus clear that the strength of such winds is due to the steepness of the atmospheric gradients of pressure, and not to the speed at which the earth's surface at each point travels round its axis. However, as has already been pointed out, the higher the latitude the lower the velocity need be to maintain the gradient.

CHAPTER VII.

CYCLONES OR ATMOSPHERIC WHIRLS.

MANY meteorologists have expressed their inability to conceive the nature of the forces which result in the development and movement of cyclones, some attributing the low pressures at the centres to the action of the rotating wind, whilst others attribute the rotating wind to the low-pressure centres. Matter entering the atmosphere which does not partake of the angular velocity of the air may be the cause of certain high-level winds ; but it is not possible to see how the dominant winds could be produced in this way. However, such particles or corpuscles might in some way heat the atmosphere and give rise to local differences of temperature, just as do the light and heat rays of the sun. Indeed it has never been shown that there is any force acting on the atmosphere which could keep the dominant winds in motion except the direct or indirect local heating of the air.

In these circumstances we are driven to conclude that the general winds result from differences of density due to differences of temperature. We thus have gradients of density set up, down which the air flows, its velocity being related to the steepness of the gradients ; but the actual directions the winds take in flowing down these gradients are largely the result of the earth's rotation.

The force with which the air tries to recede from the low-pressure centre of a cyclone is dependent on three things:—

(1) The centrifugal force due to the curvature of the isobars.
(2) The deflecting effect due to the earth's rotation.
(3) The angle at which the air is climbing up or down the density gradient owing to its momentum.

The first and third of these are independent of the latitude of the cylcone, but the second is greater the higher the latitude. Observation and calculation show that in all cases the forces controlling the velocity of the wind, and the steepness of the gradient, are in a reasonably well balanced condition.

Any air movements set up either by mechanical or other means gradually die down as a result either of internal friction or of friction against land or water, and on account of this all winds die down with comparative rapidity when the driving force ceases to act. All secondary cyclones thus disappear in comparatively short time. However, the great Polar cyclones, especially the Southern one, persist the year through, their centres covering areas over which the air is being heated in a continuous but variable manner.

In this connection it is not quite correct to speak of the heating of the Polar cyclones as being continuous ; for they vary in strength considerably in a very irregular manner from day to day and year to year. It is necessary, therefore, to infer that the heating agent which gives rise to them is of an irregular character.

When there is an air density gradient in the atmosphere the movements set up by it are not directly from high to low density areas, but take place in the form of great whirls, as shown in Fig. 46. In this chapter the causes of the changes of density which produce the whirls will not be considered. Attention will be confined to the curved paths the winds take, and why these curved paths exist. All air and water movements are drastically affected by the rotation of the earth. The control thus effected does not add to or subtract from the energy of the winds by changing their velocity ; the effect is to change their direction, and prolong the life of low- and high-pressure areas, by giving rise to cyclonic and anticyclonic movements, the areas occupied by which level-up comparatively slowly as a result of viscous friction and cooling.

A number of cyclones have already been figured. Some are very large indeed, the Antarctic cyclone covering the greater part of the Southern Hemisphere in latitudes higher than 40° ; but numerous smaller cyclones develop and disappear again in the areas covered by the greater cyclones, and these smaller secondary cyclones generally move along with the air of primary cyclones or bordering anticyclones.

We shall see that secondary cyclones, especially, are not all built up on exactly the same pattern ; for the directions of the winds and the temperature distributions in them, although obeying Buys Ballot's law, are of a very variable character.

It is not an easy matter to explain without mathematical treatment the effect of the earth's rotation on moving bodies on its surface. The effect of this rotation is really to change the direction of the moving air without altering its

velocity. Ordinary acceleration, such as a motor-car experiences when the accelerator pedal is moved, is called "tangential acceleration." When the steering wheel is moved, the car, however, alters its direction, but not its velocity. This steering effect has been called "radial acceleration"; for the new force brought into play is towards the point around which the car is circulating, *i.e.* along the radius.

The simplest illustration of radial circulation is that of a ball swung around a centre to which it is attached by a cord of fixed length. The actual velocity of the ball is (or may be) the same at every instant. If it were left to

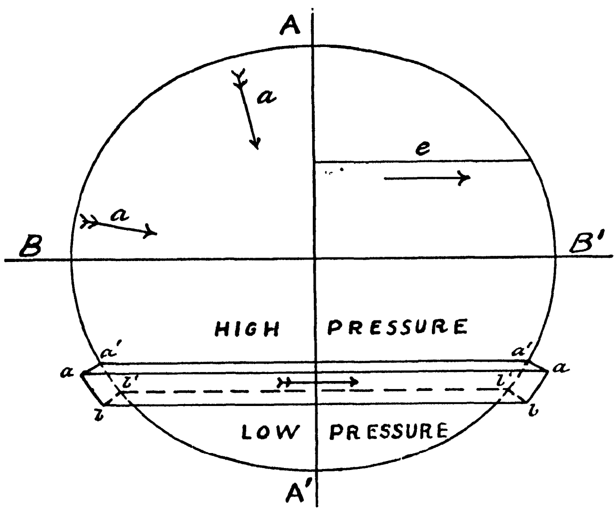


Fig. 48.—Showing Results of Earth's Rotation.

itself (that is, if the string were cut) it would move away from the centre (tangentially) in a straight line with unaltered velocity. But so long as the string is sound this is prevented by the pull of the cord, which compels the ball continually to keep at the same distance from the centre.

One or two points must be noted here which are apt to give rise to misunderstanding. In the first place, in the case just described, when the ball is held by a string, although it is accelerated towards the centre, it does not actually move towards the centre. The acceleration is always at right-angles to the direction of motion, and therefore in a direction in which there is no motion. Here, therefore, we have acceleration without change of velocity.

In actual cyclones this condition is seldom realised. At the earth's surface the movement generally is a spiral one

towards the centre ; but higher up, near the top of the troposphere, the movement is spirally from the centre, but is still in accordance with Buys Ballot's law.

The manner in which the rotation of the earth affects the directions in which the winds blow will be seen from the following considerations. If the earth did not rotate upon its axis it would be approximately spherical in form. However, owing to its rotation, the equatorial regions are caused to bulge outwards somewhat and the polar areas are flattened. The gravitational forces tending to make the earth assume a spherical form have superimposed upon them the centrifugal forces resulting from its rotation.

This effect of the earth's rotation is shown in Fig. 48. A A' is the polar and B B' the equatorial diameter, and the oblate spheroid is the earth. Now gravity is drawing all parts of the earth together in the directions shown by the radially directed arrows a ; and if the earth were not rotating on its axis A A' it would be a true sphere. However, it is rotating about its axis, and an outward or centrifugal force is acting at right-angles to the axis in the direction of the arrow e, and this force is superimposed upon the force of gravity. Its value is zero at the poles A A', and reaches a maximum at the equator B B', the value at any intermediate latitude being proportional to the distance from the earth's axis. The centrifugal force is everywhere acting on the atmosphere as well as on the earth, and therefore the atmosphere forms an almost regular layer over the surface of the oblate earth.

Now it will be seen that if any mass of air be moving in any direction relative to the earth, either up or down or sideways, the value of its centrifugal force is not in accordance with the demands of its new position with regard to the earth.

Generally speaking the winds involve large masses of air, whose re-entrant currents move approximately parallel to the earth's surface and are therefore curved. The case is different when we deal with smaller masses of air, such as those involved in tornadoes ; for in them the air moves in comparatively small masses around steep gradients.

In Fig. 48 the polar axis is A A'. A mass at the equator B B' is carried from west to east at a velocity which causes it to rotate round the earth's axis once in 24 hours, or at a speed of about 1,035 miles per hour. At the poles A A' the earth and air have no translational (tangential) velocity, and at intermediate latitudes their velocities are proportional to their distances from the earth's axis. Indeed all over the earth the atmosphere, when there is no wind, is everywhere

travelling towards the east at the same *angular* velocity. However, if the atmosphere be set in motion at any point, its angular velocity is altered and will not be that of the earth below it. On this account the air will not move along the lines of longitude or the parallels of latitude. In the Southern Hemisphere (Fig. 48), in whatever direction the air moves, as seen from the earth, it will turn away to the left so as to follow a circular path leading to the point from which it started.

Fig. 49 shows a point (a) in the Northern Hemisphere. If a mass of air at a be forced in a northerly direction by some force, such as might result from a temperature gradient, as it moves from a it reaches regions where the surface of

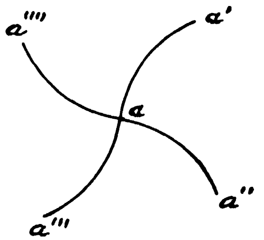


Fig. 49.—Direction of Wind Deflections owing to Rotation of Earth.

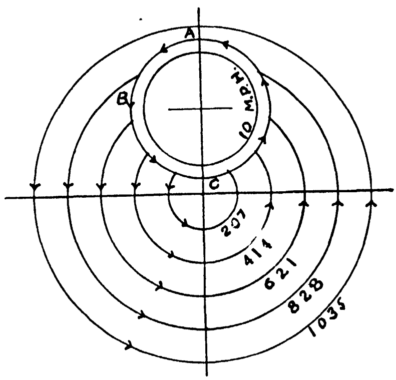


Fig. 50.—Illustrating Cyclonic Movements in Northern Hemisphere.

the earth is travelling less rapidly than itself, and it appears to anyone on the earth to be deflected towards a'. If the air at a is forced in a southerly direction, it finds itself in a region which is moving more rapidly towards the east than itself, and it is deflected towards the west a'''. When the deflecting force acts from the west, the movement of the air is more rapid than is required by the latitude, and the air is constrained to move towards the south to a'' so as to get into a position of equilibrium with the surrounding air further from the earth's axis ; but if the force acts from the east, then there is a deficiency of velocity for the latitude, and the air moves north to a''''. It will be seen that in whatever direction the air be urged in the Northern Hemisphere, the deflecting is always to the right. Similar reasoning will show that in the Southern Hemisphere the deflecting is always to the left.

(If, as is shown in Fig. 49, in the Northern Hemisphere

the air is urged towards any particular centre, the wind deflections produced are such as to cause the air to pass on the right side of the centre.

The deflecting force tending to alter the direction of the wind being equally powerful along each latitude in whatever direction the wind is moving, as the wind changes its direction the deflecting forces also change their directions so as to remain at all times at right-angles to the wind movements. This is illustrated by the arrows in Fig. 46. The deflecting force, therefore, cannot accelerate the velocity of the wind, although it changes its direction of flow, and any change in the velocity of the wind must be due to some force acting upon it other than that due to the rotation of the earth.

But it may be suggested that if a mass of air be urged from the pole towards the equator without being checked by friction, when it reaches the equator it will appear to anyone on the earth to be travelling from east to west at a velocity of 1,035 miles per hour. However, it can be shown that the conditions of restraint of the atmosphere due to the resulting pressure gradients are such that this cannot occur.

Fig. 50 is a plan of the Northern Hemisphere distorted so as to show the parallels of latitude at equal distances apart, and the velocities with which each latitude moves are given. A disc having at its periphery a square rim is shown. Now if the rim of this disc be rotated at ten miles per hour, whilst the earth's surface is either rotating or at rest, observers standing at *A*, *B* and *C* will each see the rim passing them at ten miles per hour. If the earth's surface were stationary the rotating disc would be subject to radial forces equal in all directions ; but if the surface were rotating, this would not be the case.

We have, however, been supposing the earth's surface to be flat, whereas the earth is an oblate spheroid. This point requires some consideration.

If the earth were not rotating, and a ball were placed anywhere on its surface, the ball would not move. On the other hand, if the earth were quite rigid, and maintained its spherical form when rotated, a ball would not rest quietly on its surface. It would roll towards the equator, and if the earth's angular velocity were not too great, it would come to rest at the equator. If, however, as is the case, the earth were not rigid, but when rotated assumed the form of an oblate spheroid, then the ball would rest quietly anywhere on its surface.

For example, in the case of Fig. 50, we might suppose the surface to be spheroidal, gravity being normal to the

surface everywhere. In such a case a ball placed anywhere on the surface would not move, and a disc shaped to fit the earth's curved surface would be subject to radial strains of equal strength all round.

We thus see that the oblateness of the rotating earth makes it act much as a sphere would if it were not spinning. However, there is an important difference between an oblate spinning earth and a stationary one ; for a force is introduced which increases the strength of the radial forces in the rotating disc, the force being greater the higher the latitude.

It has already been emphasised that every wind must be accompanied by one moving in the opposite direction. Even when a wind circulates round the earth along some line of latitude it will be found that this is the case. Sometimes compensating winds move side by side ; in other cases the return current is above or below the one that is being considered.

Perhaps the most simple form of circulation is that of a wind following a line of latitude. In Fig. 48, *a b a′ b′* is a section of an air current moving from west to east in the Southern Hemisphere. The air forming the ring is moving faster than the earth below, and, in attempting to turn to the left, tends to move bodily to a lower latitude. As a result the air in lower latitudes is compressed and the air in higher latitudes is expanded. Eventually the difference of pressure between the two sides prevents further displacement towards the equator. We thus have a high-pressure region set up on the equatorial side, and a low-pressure region on the polar side. As long as the westerly wind of this ring is moving at the same angular velocity over its whole sectional area it is quite stable ; for although the lower portions of the atmosphere are more dense than the upper portions, and therefore exert a greater pressure towards the equator, the lower air, on account of its greater density, requires a greater force to move it.

In such a case as that above described, the friction of the wind against the earth's surface reduces the velocity of the lower portion, and it flows towards the area of low pressure, whilst the upper portions flow towards the area of high pressure.

In the charts which have been given showing the winds and isobars, it will have been seen that the circulating air moves in spirals directed towards the central area of low pressure, where it is clear the air must rise to find room for further air. Over a land surface this deviation from a circular path has been found to average about 20° or 25°,

the greatest angle of deviation being somewhat in front of a moving depression. Over the sea the deviation is less than over the land, and is greater at night than during the day.

Fig. 51 shows a section across a hypothetical stationary cyclone in the troposphere, *A A′* being the centre round which the cyclone rotates, and *B B′* the surface of the ground. The arrows show the inward motion of the air and the vertical rise, the dotted ovals showing the direction of circulation at different levels. The wind at the level *b* is at a height of about 2,500 feet. Here the currents, as the arrows show, are circular, and the centrifugal force due to

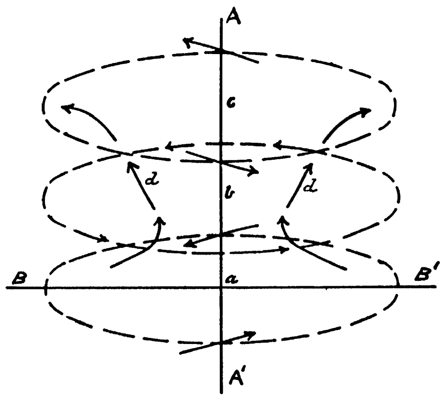


Fig. 51.—Section Across Hypothetical Cyclone.

the velocity of the air, coupled with the outward force of the "geostrophic wind" due to the rotation of the earth, just balance the pressure gradient towards the centre of the cyclone. Higher up still, at the level *c*, the winds blow out from the centre as shown by the arrows, and this outward flow extends up to and some little distance into the stratosphere. It is clear that the reason for this upward and outward movement at high levels is the fact that the winds at the surface of the ground *a* are checked by friction with the earth's surface, and as they are then not moving with sufficient velocity to balance the low pressure at the centre of the cyclone, they move outwards, rise up in the cyclone, and, as they cannot pierce the tropopause, they have to flow outwards below it. However, this spiral outward movement of air communicates by friction some movement to the air of the stratosphere, and as the resulting downward movement there, at the centre of the cyclone, cannot pierce the tropopause, it moves outward in the stratosphere. In the lower portion

of the centre of a cyclone the air is generally too cold and heavy to rise, and as a result there is no condensation there with formation of cloud, and the air is generally calm and clear.

But there is friction between all layers of air moving at different velocities, and as such varying velocities exist throughout all cyclones, there is friction everywhere as well as near the earth. On this account the energy of the circulating air is slowly but steadily dissipated, the velocities of the winds decrease, and the cyclones fill up and disappear, unless they are supplied with fresh energy from some external source. However, as is the case in middle and high latitudes, when warm moist air is carried along the earth's surface in opposition to the density gradient, and the air is disturbed by cyclones, some energy may be imparted to the cyclones by the condensation of aqueous vapour where the air is rising and rainfall occurring. But this cannot be the source from which cyclones derive their energy, for they often form and disappear without rainfall resulting.

The great cyclone of the Southern Hemisphere, the winds of which are known as the "raging forties," lasts the year round, and must receive a constant supply of fresh energy. However, even in the case of this great cyclone, the winds wax and wane without reference to the seasons.

We have so far treated air currents as resulting from gradients due to differences of pressure. In Fig. 51 the dotted lines may be regarded as isobars. The arrows showing air currents at the level *a* are inclined to the isobars, and point inwards, because the winds they represent have lost velocity by friction with the ground, and the moving air has insufficient centrifugal force to balance the pressure. By moving down the pressure gradient the air suffers acceleration, and the balance between the outward and inward forces is maintained. However, in the case of a cyclone, both the pressure gradients and the velocities undergo changes, and the relationships between the various forces are somewhat complex.

The points of interest in the relationships between density and pressure are that the pressures in a given mass of air may result from variations of density in another distinct mass of air higher up, or even lower down. Thus if the air of the stratosphere be heated, and no such temperature change is made in the troposphere, the air of the stratosphere expands and rises to form a dome at the upper limit of the atmosphere, and the air of this dome spreads outwards. This reduces the weight of the whole column, and the

barometric pressure at the ground surface falls. As a result there is an inward movement of air in the troposphere, the effect of the earth's rotation deflects this air, and a cyclone is formed in the troposphere.

If the air be dry and cool near the earth's surface, as it moves inwards and upwards it expands, and may form a heavy central column which tends to check the upward movement. W. H. Dines gives a section across a cyclone which shows that this actually takes place (Fig. 52), and

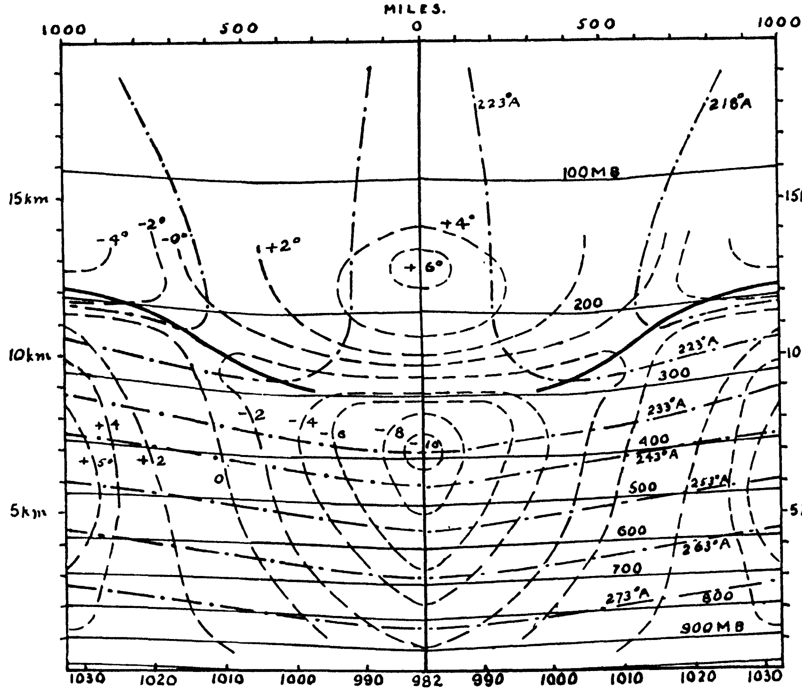


Fig. 52.—Section through Cyclone, after W. H. Dines.

proves that under average conditions the pressure gradients of a cyclone in the troposphere are actually acting to some extent in opposition to the air circulation there.

The uprising air masses which produce rain in a cyclone are generally near the front margin ; but they may be elsewhere. However, cyclones present many features and differ greatly the one from the other.

The section of a cyclone shown in Fig. 52, after W. H. Dines, is founded upon 250 soundings of the atmosphere. Doubts have been expressed as to the correctness of the results given by this collection of soundings, but no figures have been published to prove that such doubts are justified. It

will be seen that the coldest point in the troposphere is about 7 kilometres from the ground over the centre of the cyclone, and that the warmest region forms a band round the cyclone, at about the same height, at a distance of 1,000 miles from the centre. According to the old theory the temperature conditions should be the reverse of this. In the stratosphere the conditions are also the reverse, the warmest point being at a height of about 13 kilometres, whilst the coldest region is at the same height and forms a cold band above the warm one in the troposphere below. In the present author's view this section of a cyclone is in good agreement with other facts.

CHAPTER VIII.

THEORY OF THE WINDS.

In previous chapters much has been said concerning the physical laws which show us what are the effects on the winds of the earth's rotation and changes of atmospheric temperature, density and pressure; but before discussing the "theory of the winds" it will be advisable to restate some of the principal points touched upon in previous chapters, and also mention other relevant matters.

It must be remembered that the gaseous envelope of the earth relatively is very thin indeed. Half its mass is within four miles of the earth's surface, and as the radius of the earth is about four thousand miles, one half the mass of the atmosphere is contained in a thickness which is only a thousandth part of the earth's radius, and about one fifteen-hundredth part of the distance of the equator from the poles. The highest mountains exceed a height of four miles only in a few instances, and there are few plateaux exceeding three miles in height. The small thickness of the atmosphere as compared with the size of the earth is almost as marked when we take three-quarters of its mass instead of one half; for more than this weight is within a distance of seven miles of the earth's surface.

Diagrams drawn to show vertical differences of pressure and temperature necessarily have the vertical heights very greatly exaggerated as compared with the horizontal distances, with the result that the gradients of pressure and temperature appear in drawings to be vastly steeper than they actually are. Care should be taken not to be misled by this fact. Indeed, owing to neglect of this consideration it has been imagined in many instances that small and weak local temperature disturbances are capable of producing much more marked distant effects than they are actually capable of. For example, typhoons and cyclones, however large or small, must derive their energy mainly, if not entirely, from strictly local sources.

The comparatively small thickness of the atmosphere as compared with its area is thus not always given the notice

it deserves ; for theories which seem reasonable when this is overlooked will be seen to be quite untenable when the actual proportions of cyclones, great and small, are realised.

In a thin atmosphere any rise of the air must take place in the immediate neighbourhood of the place where it is hottest, and any fall of air must occur where the heating is least. Heated masses of rising air draw in surrounding cooler air, and descending cold air forces sideways warmer air. In this manner cyclones and anticyclones are formed. Indeed, so thin is the atmosphere, that it does not matter at what level the cooling or heating takes place, providing the heated or cooled stratum is not very thin indeed. Thin layers, however, only produce local effects as regards the flow of the winds, and their effect upon the isobars is generally almost inappreciable.

On account of its very small thickness as compared with the large area it covers, the atmosphere is very sensitive to local influences, and it is difficult to conceive that differences of temperature between areas widely separated can produce cyclones thousands of miles from the heated areas. Indeed, we must be prepared to adopt the view that as the temperature gradients on the earth's surface in middle latitudes are such as would produce density gradients in opposition to the directions in which the prevalent winds blow, there must be compensatory density and temperature gradients at higher levels in the atmosphere to cause our prevalent winds. In low latitudes the lower "trade winds" are the result of density gradients favouring winds blowing towards the equator, whereas the "antitrades" are caused by a density gradient at a higher level favouring winds from the equator. In middle latitudes the temperature and density gradients in the troposphere favour winds on the earth's surface blowing towards the equator ; but as the prevalent winds actually blow in the opposite direction, there must be temperature and density gradients in the higher atmosphere strong enough to overpower the lower gradients and produce the actual surface isobars.

The earth, as we know, is not a true sphere. It is a very slightly oblate spheroid, the equatorial diameter being about 26 miles greater than the polar diameter. This flattening of the polar areas has evidently affected the solid earth as well as the liquid oceans ; for it cannot be said that the distribution of land and water shows any close relation to the polar axis. Indeed we find that the depth of the seas and the heights of the mountains are the result

of differences of density in the crust within comparatively small distances from the earth's surface.

If the crust of the earth within a hundred miles of the surface had the properties of glacier ice, there would be no mountain chains, plateaux, continents or islands. Gravity would cause the crust to flow until the earth became a regular, comparatively smooth, oblate spheroid, and the water would spread over it as a layer of nearly equal thickness throughout. But the rocks of the earth's crust are more or less soft solids, not viscous liquids like glacier ice, and they vary in density even at very considerable depths. It is to the variable horizontal density of the crustal, and immediately subcrustal, rocks, their rigidity, and the erosive power of running water, that the surface irregularities of our globe are due. The continents, plateaux and mountain ranges rest upon low density, and oceans upon high density, rock foundations. In fact the elevated areas float like ice floes upon the ocean. The rocks being solid, and not liquid like glacier ice, gravity is unable to pull the land surface to a very gentle undulating form corresponding to that required by the rock densities beneath. However, the solids forming the crust can in many instances bear stresses of such magnitudes that the existence of deep valleys and steep mountain slopes is possible. Where denudation is rapidly removing material to new localities, and no variation is taking place in the density of the subcrustal foundations, the crust distorts itself to secure a balance between rigidity and stress, and the resulting vertical movements produce faults, rock folds, etc., as well as the spreading of elevated areas.

According to this view the positions of mountains and ocean depths are reflections of the density conditions of the earth beneath them, and for unknown reasons the distribution of areas of high and low densities must be changing and their positions and magnitudes varying ; for mountain chains and deep seas in the past have changed places, or deep seas or mountains formed in new localities. Denudation cannot wear down mountain chains, nor can deposition fill up deep seas. It is true that denudation may bring to the surface denser rocks, and result in the deposition upon the ocean bottoms of materials of less density than the rocks from which they were derived, but the amount of material that would have to be moved to bring about a condition of equilibrium would have to be very great indeed.

Over the atmosphere and oceans, which are fluid, gravity

has complete control. Air and water cannot do otherwise than strive to spread over the earth until gravity's requirements are everywhere satisfied ; but where there is continued local heating going on in the atmosphere or the oceans a state of repose is never reached. The force of gravity, as we know, is not everywhere the same on the earth's surface. It is greater at the poles than at the equator, and varies locally in accordance with the density of the rocks forming the crust or subcrust.

Given an even temperature throughout the atmosphere, and a density resulting from the influence of gravity, there is no reason to suppose that there would be any air movements. The atmosphere would then be a motionless saturated fluid, and it would rest upon ice, water and rock. From this inactive condition the atmosphere and oceans are rescued owing to the variation of insolation with latitude, and by radiation of heat again into space, especially during the night. The amount of energy received in the form of heat, light and other radiations varies from hour to hour throughout the day, and becomes less and less at the earth's surface as we move from low to high latitudes. Irregular heating also results from the varying inclination of the sun's rays, throughout the day. We thus get our seasons, winter in the Northern Hemisphere coinciding with summer in the Southern Hemisphere, and *vice versa*, and our temperature differences between night and day.

Varying horizontal temperature differences are thus set up in the air, and the state of equilibrium of the atmosphere is destroyed by the resulting differences of air density from place to place. In its attempt to get rid of such irregular horizontal differences of temperature and density, movements are set up, and winds are the result.

It is sometimes stated that irregular horizontal distributions of temperature and density only occur in the troposphere. However, there is no valid reason for supposing that this is the case ; and there is now proof that the stratosphere is irregularly heated, just as is the troposphere. That there are high winds in the upper as well as the lower atmosphere is certain.

It has already been stated that when pressure gradients are produced by irregular insolation, air movements down the gradients are not direct, the actual paths being spiral or cyclonic in character owing to the earth's rotation. Further notice must now be taken of this.

Every particle of the earth is rotating once in twenty-four hours, as well as revolving round the polar axis. In fact,

whatever size mass we take, we must regard it as revolving round an axis parallel with the polar axis. This is true in the case of the solid earth ; but the conditions are different when the substance considered is a fluid, or is a pivoted mass as in Fig. 50. In such a case as this, if the earth revolves, the pivoted disc to anyone on the earth appears to rotate, and turn round once in every twenty-four hours ; for as it is carried with the earth the point of support is at the centre of gravity of the disc. Every part of every air current is thus influenced by a force acting at right-angles to the direction of its motion, and as the direction of the current of air changes, the direction of the deflecting force also changes.

The problem is a very complex one, and difficult to make clear. However, the fundamental truths which it is necessary to grasp must have been impressed upon the minds of all who have, in youth, spun a top, or examined and experimented with a gyroscope in later years.

A spinning top impresses one as being a most perverse object. Give its projecting axis a gentle push, and instead of obeying the impulse it quietly moves off at right-angles. In the case of the spinning earth, the reason why its axis of rotation moves very slowly from a point near the pole star (*Polaris*) is that it is obeying the same laws as the spinning top.

Try gently to alter the direction of the top's axis of rotation when it is spinning slowly; the top wobbles and the point upon which it spins describes circles on the ground. Now the axis of the earth also wobbles, but very slowly, the force producing this wobble being the attraction of the sun on the equatorial bulge. The movement is known to astronomers as *precession*, and the earth takes 25,800 years to complete one wobble!

Although very many pilot balloon ascents have been made, and the manner in which temperature varies with height is fairly well known in the case of the troposphere, our knowledge of the actual average temperature gradients is confined to a few localities only. With the aid of this knowledge, however, an attempt will be made to show how the isotherms rise and fall in the atmosphere between the poles and the equator. It must be understood that this cannot be done with exactitude, for the gradients are not the same along all lines of longitude. The gradients of density obtained will be compared with the known wind directions in order to ascertain to what extent they are in agreement, due attention being paid to the effects of the

earth's rotation. This can only be tentatively carried out, the facts required for proper scientific treatment not being available.

It is generally tacitly assumed by meteorologists that a "wind" is an air current moving parallel to and not far from the ground. Thus, when a mass of air has a vertical motion as well as a horizontal one, it is called an ascending "current," not an ascending "wind." This definition would make it impossible for us to say that there are "winds" in the stratosphere. However, this definition of a "wind" is not strictly adhered to; for air currents that are called "winds" often rise and fall considerably, passing under or over each other. Masses of rapidly moving air, even when high up in the stratosphere, are here referred to as "winds."

Admiral Beaufort drew up a scheme showing a definite relation between the velocity of the wind and the character or name given to it. Table VIII shows this scheme, which is still used to furnish an approximate idea of wind velocity, and to enable its value to be plotted on a chart. However, it is usual for most purposes to state the wind velocity merely in miles per hour or metres per second.

On many meteorological charts where the winds are shown by arrows, the number of feathers in the arrow indicates the number on Beaufort's scale, and this enables the velocity of the wind to be shown in a simple manner.

TABLE VIII.

Beaufort Wind Scale.

Scale No.	Character of Wind.	M.P.H.	Scale No.	Character of Wind.	M.P.H.
0	Calm . .	0	7	High wind .	32 to 38
1	Light air .	1 to 3	8	Gale . .	39 - 47
2	Slight breeze .	4 - 7	9	Strong gale .	48 - 54
3	Gentle breeze .	8 - 12	10	Whole gale .	55 - 63
4	Moderate breeze	13 - 18	11	Storm . .	64 - 75
5	Fresh breeze .	19 - 24	12	Hurricane .	Above 75
6	Strong breeze .	25 - 31			

So far reference to what is taking place in the atmosphere much above the surface of the ground has been avoided. Some facts, however, have had to be given concerning the "free atmosphere" to make surface phenomena clear. We must now deal with the atmosphere as a whole; for the

winds of the earth really blow at all levels and influence each other everywhere.

For many years for a knowledge of the temperature of the "free atmosphere" we had to rely upon observations made with the aid of kites, on mountain slopes and summits, and in manned balloons. Even in those early days it was recognised that the results obtained were not such as had been anticipated, and many meteorologists, for theoretical reasons, doubted whether the observations could really be relied upon as indications of temperature conditions existing at higher levels ; but it became more and more clear as facts worthy of confidence accumulated that the theories commonly held concerning the phenomena exhibited by cyclones, especially in middle and high latitudes, were not as dependable as had been imagined.

We need not consider in any detail the history of the exploration of the atmosphere by sending up small rubber registering balloons filled with hydrogen gas, having attached to them light instruments for recording temperatures and pressures (in England the form of instrument generally used has been the Dines Meteorograph). Such balloons reach heights extending well into the stratosphere. Thousands of ascents have been made by these instruments, and the information gained is such that, to some extent, the ideas formerly held regarding the composition of the upper atmosphere, circulation of the air in cyclones and the distribution of temperature in them, have had to be given up.

We all know that climates are as remarkable for their regularity in some areas as they are for their irregularity in others. Between the "horse latitudes," in equatorial regions, except in the region of the Indian monsoons, the most marked seasonal changes are variations in the rainfall, temperatures and pressures being remarkably equable the year round, except over the Indian Ocean. However, in middle and high latitudes the seasons are very marked both as regards changes of temperature and pressure. But the seasonal changes here are not of a regular character. Winters and summers come and go ; but we have summers and winters notable for being either cold, warm, dry or wet. It thus comes about that it is necessary to base our ideas of climate upon average as well as upon temporary conditions. Looked upon from this point of view we find that secular seasonal changes are very slow. Indeed it would seem that no considerable change of climate has occurred during the last hundred years. However, the

advances and retreats of Swiss glaciers do seem to indicate changes not brought out by our recorded figures of temperature and humidity.

Free atmospheric observations, as already remarked, have been insufficient in number and have not extended to sufficient heights, for a really satisfactory study of the upper atmosphere to have been made. However, much can be learned from the few thousand records obtained, and especially by a study of individual free atmospheric soundings and comparing them with surface conditions.

We have seen that the temperature of the troposphere is largely due to the heating of the lower atmosphere by the sun's rays. A considerable portion of this heating is due to the interception of heat and other rays by water vapour, cloud, carbonic acid gas, dust, etc. There is also to be considered the contact of the air with water surfaces and the sun-heated ground. The absorption of water vapour is very important indeed, for it involves both the latent heat of melting and of evaporation. As the temperature falls rapidly to below the freezing-point at no great height above the sea, this latent heat is soon nearly all given up, warms the air, and retards the fall of temperature as the air rises and expands. It has been proved that the height at which the temperature ceases to fall (the tropopause) is higher the greater the earth's surface temperature, the higher the barometer, and the greater the humidity.

There is good reason to believe that some of the radiations from the sun, probably material, which are capable of heating the atmosphere, are incapable of directly affecting it much below the tropopause. This matter will be considered later.

The records of the temperature gradients in the atmosphere obtained by means of balloons carrying meteorographs thus make it appear that the actual thickness of the troposphere varies in some measure in sympathy with the varying conditions of temperature, pressure and humidity near its base ; but this may be fortuitous. No two records, even for the same locality, quite agree, the irregularities being very marked in the stratosphere as well as in the troposphere. In the lower two miles of the troposphere, chiefly owing to greatly varying humidities, clouds, etc., the temperature gradient is generally very irregular. When the air is clear at night, considerable radiation takes place near the ground, with loss of heat, and the temperature gradient is then often reversed. The same result is often produced in high latitudes or where cool

winds undercut warm ones, and also locally where clouds intercept the sun's heat rays.

It is proposed to give some examples of the mean records obtained by the use of meteorographs, and to compare them with theoretical convective equilibrium curves of dry and saturated air.

It is well to remember that although the main cause of differences of density in the atmosphere is temperature difference, variations of humidity also result in density gradients of a much less pronounced form ; for although aqueous vapour has only about half the density of air, even in summer at the earth's surface, when the air is saturated, the volume of vapour forms only a fractional part of the air. However, the high specific and latent heats of water in its various forms profoundly affect the temperature conditions of the troposphere, and therefore also its density.

Perhaps the most important feature of the low density of water vapour is that it, and the air with which it mixes, rises in the surrounding atmosphere, and carries up with it the latent heat of evaporation. In the atmosphere this is constantly going on, and is a potent cause of the establishment of approximate convective equilibrium conditions. The lower portion of the troposphere thus acts like a sponge, constantly soaking up moisture from water surfaces, damp ground and vegetation, the "sponge" eventually being compelled to give up its moisture, owing to the air movements in cyclones, the cooling effect of rising winds on mountain slopes, and the loss of heat by radiation as the winds move towards the poles.

The absolute temperatures centigrade of the troposphere ascertained for a number of European stations are shown in Table IX. The figures are based upon the facts ascertained by many hundreds of balloon ascents, and on this account show more regular gradients of temperature than do independent ascents. The lowest mean temperature, or approximate position of the tropopause, for each station is printed in italics. It will be noticed that the level of the lowest temperature varies, being as a rule lower in high latitudes and higher in low latitudes. The warmest minimum point is at a height of 11 km. over Abisco in the north, and one of the coldest minima at a height of 12 km. over Pavia in the south. We thus see that the highest of these minimum temperatures occurs above the most northerly station and the lowest above the most southerly station. The fact must not be lost sight of, however, that the mean temperatures shown in Table IX are to some extent

TABLE IX.

Variations of Temperature with Height.

Europe.

Station.	Latitude.	Temperature C° Abs. less 200.																
		Sur-face.	1 km.	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Abisco	68° 20′	73·7	71·0	65·8	60·7	55·3	49·2	42·4	35·4	28·4	22·9	20·3	*20·2*	21·5	22·1	22·0	21·8	22·0
Pavlovsk	59° 0′	74·9	71·0	66·7	61·3	55·7	49·8	43·3	37·1	29·8	24·4	21·3	*20·0*	20·7	23·4	23·5	...	...
Moscow	55° 45′	77·0	74·4	70·2	66·2	60·3	54·2	47·7	40·8	32·9	25·7	19·8	*16·8*	18·7	21·6	21·0	21·2	...
Hamburg	53° 35′	79·9	75·4	70·4	64·8	59·1	52·6	46·2	39·7	33·5	27·7	22·5	19·2	*18·4*	20·2	19·4	20·2	20·8
Berlin	52° 32′	80·1	76·8	71·7	66·9	61·0	54·8	47·9	40·8	33·1	26·8	21·9	19·2	*18·3*	19·3	18·7	17·9	17·6
England	51° 39′	...	78·0	73·2	67·7	61·7	54·8	47·8	40·7	33·6	27·5	22·2	19·6	18·8	*18·7*	18·9	...	...
Uccle	50° 49′	79·6	77·1	73·0	67·8	62·0	55·3	48·5	41·5	34·4	27·7	21·7	17·5	16·4	*15·3*	16·4	16·4	...
Paris	48° 51′	80·7	78·5	74·5	69·8	64·3	58·1	51·4	44·3	36·9	30·0	24·3	20·2	19·5	19·3	19·1	18·9	16·3
Strassburg	48° 35′	81·3	78·2	73·8	68·4	62·4	56·1	49·3	42·1	34·8	27·8	22·3	18·1	*16·8*	17·6	17·9	18·2	20·1
Vienna	48° 12′	81·0	77·6	73·0	67·6	61·9	55·6	48·8	41·2	33·6	26·9	21·8	18·4	*18·3*	19·6	19·6	20·1	20·4
Munich	48° 8′	79·9	79·0	74·4	68·8	62·7	56·6	49·9	42·9	35·7	29·1	23·8	20·0	*17·2*	18·2	17·3	19·8	19·9
Zurich	47° 27′	82·0	78·8	75·9	69·9	63·9	57·2	49·9	42·3	34·5	27·9	23·1	17·1	16·2	16·7	*15·9*	16·2	...
Pavia	45° 11′	84·6	80·7	75·1	69·2	62·9	56·2	49·4	41·2	33·9	27·3	22·7	18·5	*16·1*	16·4	17·7	17·1	18·9
Mean temperatures (A)		279·6	276·6	272·1	266·9	261·0	254·6	247·9	240·8	233·5	227·0	222·1	218·8	218·2	219·1	219·0	218·9	219·5
Mean Lapse Rates			3·0	4·5	5·2	5·9	6·4	6·7	7·1	7·3	6·5	4·9	3·3	0·6	−0·9	0·1	0·1	−0·6

misleading ; for the lowest temperature over each station shown in Table IX is the mean of the temperatures ascertained by a number of ascents, some of them being above and some below the actual tropopause. This matter will receive further attention.

The fact that at a certain height—the height of the tropopause—the temperature ceases to fall, or falls much less rapidly, is of very great interest. To make this clear, although for the reason above given the comparison is not quite sound, we will compare the actual measured mean

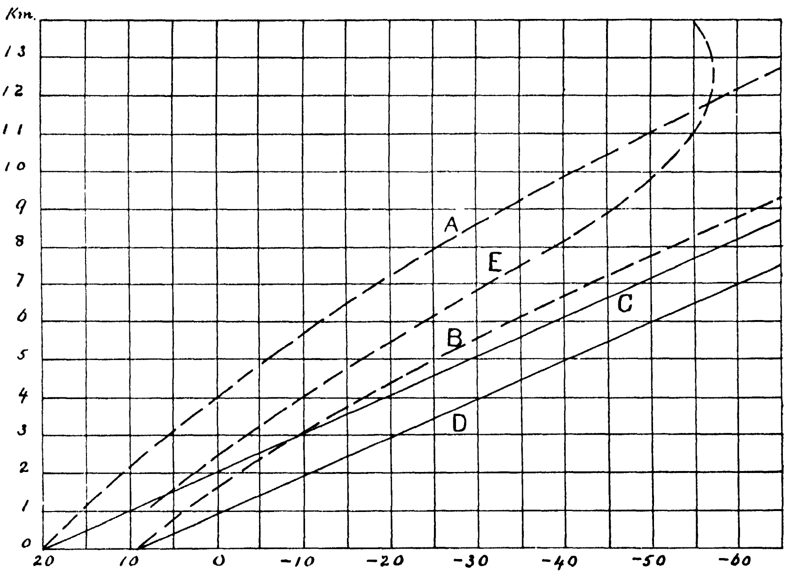


Fig. 53.—Adiabatic Lapse Curves—Dry and Saturated Air.

temperatures (*A*) shown in Table IX with some theoretical values for expanding air. In Fig. 53 curves *C* and *D* are for the adiabatic expansion of *dry air*. The usual figure for the fall of temperature, the temperature lapse rate for dry air, is taken as 1° C. for every 101 metres rise, or 9·9° C. for each kilometre. It must be noted that this decrease of temperature is the same whatever the barometric pressure may be, or whatever the height above sea-level. Curves *A* and *B* give the temperature change when the air is saturated with moisture, and represent theoretical figures.

If saturated air were rising from the ground vertically, chilling and condensation would result as it began to expand. The drops of water in the cloud formed would grow larger and larger, and, when they were big enough to fall more rapidly than the rate at which the air was rising, the moisture

would come down as rain. This condensation would go on until practically all the moisture was given up at about $-60°$ C. But it must be remembered that the rain or snow would fall through rising air below and chill it. On this account the amount of heat actually given up to the rising air by condensation would be that given up if all condensation took place over the place from which the air was rising. As a matter of fact no agreement has been come to as to how the adiabatic lapse rate for rising saturated air should be calculated. For the present purpose rigid accuracy on this point is not necessary, however, and the temperature change for saturated air is regarded as that shown by the dotted curves *A* and *B* in Fig. 53. The mean temperature curve *E* for Pavia has been shown on the figure and it will be seen that it is somewhat similar to curves *A* and *B*, but at high levels, where the tropopause should be, it represents the mean of stratosphere as well as troposphere figures.

When saturated air is rising and being chilled, there must be a downward current somewhere else, the temperature of which is increasing. This is the case when a wind blows over a range of mountains. In the case of a high range we may have ascending saturated air on one side and unsaturated descending air on the other. As the air rises rain falls on the mountain slope and heat is liberated, the result being that the air when it passes over the summit and finally reaches the bottom of the reverse slope is actually many degrees warmer than it was when it commenced to rise. This appears to be the most suitable condition for ascertaining the temperature change of rising saturated air.

That our atmosphere in most places is clear and moderately dry is due to the transporting power of the winds. They are constantly removing damp air from above oceans, seas, etc., throwing the moisture down again as rain on mountain slopes or from cyclones, and descending again as unsaturated air.

When the air at the earth's surface is dry (see Fig. 53) and has a temperature of 10° C., on rising to a height of 4 kilometres its temperature falls to $-30°$ C., but the same air when saturated with water vapour rises, as shown by the dotted curve, to a height of about 5·6 kilometres before reaching this temperature. At the ground level the vapour pressure is 9·2 millimetres of mercury, but at a height of 5·6 kilometres this vapour pressure had fallen to 0·4 millimetre, *i.e.* by nearly 96 per cent. Starting at a ground temperature of 20° C., when the air is dry, the temperature

falls to $-30°$ C. on reaching a height of 5·1 kilometres. The same air when saturated with moisture reaches a height of about 8·6 kilometres before the temperature falls to $-30°$ C., the vapour pressure falling from 17·4 to 0·4 millimetre of mercury.

It is seldom that the rising air at low levels is quite saturated with water vapour. When it is not it rises until the saturation point is reached, and then may continue to rise nearly along a saturation convective equilibrium curve.

On the diagram Fig. 53 the mean temperature curve *E*

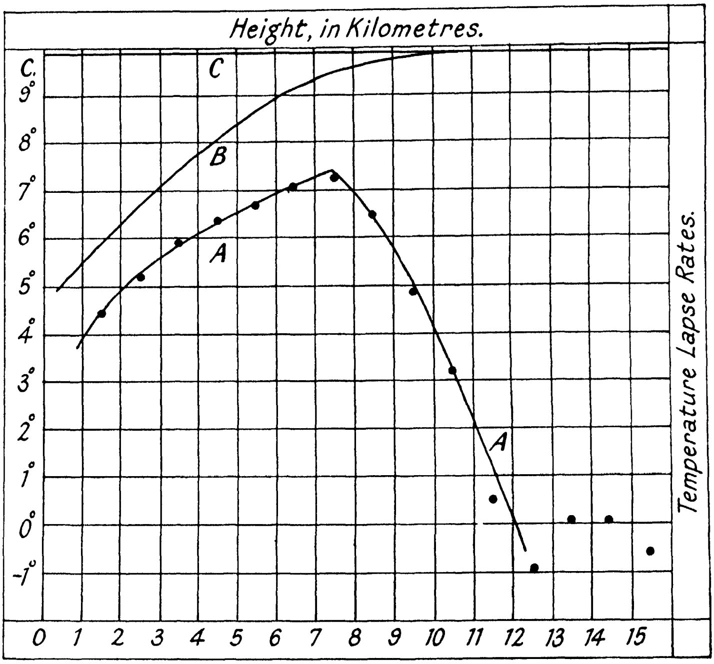


Fig. 54.—Mean Lapse Rate for Europe.

for Pavia in Italy has been drawn, as already stated. This curve represents the mean of the results obtained from a large number of ascents. It lies in its lower portions between the curves *A* and *B* for saturated air.

The temperature lapse rate of the atmosphere is a very important indication of how the air is affected by insolation, radiation and adiabatic expansion, and of the resulting movements of air of varying density to get as nearly as possible into a condition of equilibrium. The air movements set up to effect this constitute the winds of the earth.

In Fig. 54 the line *C* shows the lapse rate of 9·9° C. for dry air. For saturated air, at a ground temperature of

4·5° C., the lapse rate is shown by curve *B*. Curve *A* represents the average lapse rate of the air of the troposphere for all the stations of Europe shown in Table IX. This curve after rising with increasing height suddenly commences to fall at about 7·5 km. and reaches zero at about 12 km.

This change in the temperature lapse rate from an increasing to a decreasing rate at a height of 7·5 km. would seem to indicate that we here encounter the effects of the change which ultimately checks the fall of temperature with height at the level of the tropopause. When we are dealing with the actual lapse rate as shown by the results of individual sounding balloon ascents the curve below the tropopause differs somewhat from that shown in Fig. 54.

To ascertain the lapse rate of the upper troposphere, the tropopause may be used as a base line and the lapse rate for some kilometres below it ascertained. For this purpose individual sounding balloon ascents must be used.

A number of such soundings have recently been made at Abisco, and thirty of these, which show the position of the tropopause clearly, have been selected for examination. Table X shows the figures obtained. The soundings were divided into three groups of ten each, the mean tropopause temperature (*A*) of each group being given in the first column and the lapse rate below the tropopause in succeeding columns.

TABLE X.

Soundings showing Lapse Rates with Respect to Tropopause.

(*A*)	0·5 km.	1·5 km.	2·5 km.	3·5 km.
211·5	4·9	7·7	7·6	7·8
220·5	4·5	7·3	7·3	6·8
222·7	4·4	6·1	6·8	7·1
218·2	4·6	7·0	7·2	7·2 Means

The mean height of the tropopause was 9·7 km. when its mean temperature was 218·2° A.

Using the same thirty soundings at Abisco the lapse rate from the sea upwards was found to be as follows:—

1·5 km.	2·5 km.	3·5 km.	4·5 km.	5·5 km.
4·91	5·41	6·13	6·21	6·96

These figures are plotted on Fig. 55, the full line being

the lapse rate from the sea-level upwards and the dotted line the lapse rate from the tropopause downwards. These curves show that the lapse rate does begin to decrease three or four kilometres before the tropopause is reached, but in not so pronounced a way as the mean temperature curve in Fig. 54 indicates. This can only be the result of heat coming downwards from above into the troposphere in some form or other. From these results it would appear that the tropopause is merely the height at which the amount of heat due to external causes is sufficient to check

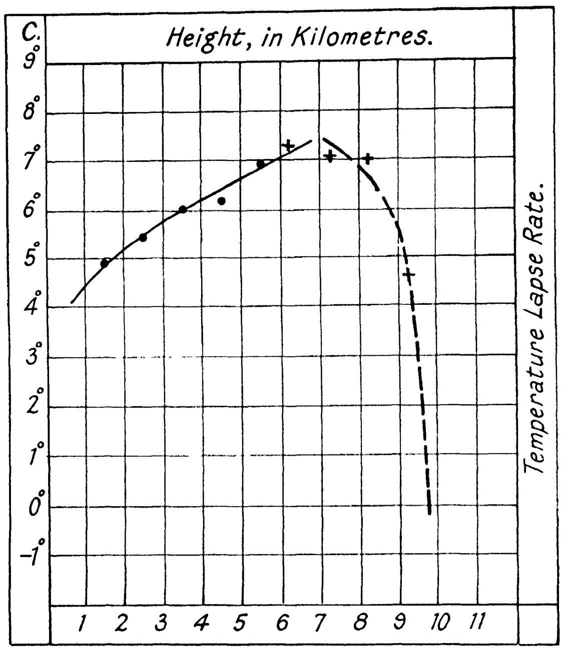


Fig. 55.—Operative Temperature Lapse Rate at Abisco.

completely the fall of temperature due to convection currents, etc. from below.

When we find the winds blowing in unexpected directions we may consider them as criteria for modifying our conception of the probable temperatures of unexplored portions of the higher atmosphere. Indeed the question of the criteria upon which our judgment may be based must depend upon the lines of study we individually follow ; and there are good reasons for considering that the directions of the winds do furnish us with valuable criteria for a study of the temperature distribution at very high levels.

The only possible explanation for the air not continuing to fall in temperature approximately adiabatically until it

reaches the upper limits of the atmosphere, where the temperature by hypothesis should be about 4° C. Abs., and often actually rising again, is that powerful material radiations from the sun must be intercepted by the atmosphere at high levels. But the most remarkable feature of following this method of reasoning is that the heating of the upper atmosphere must be mainly over the poles, and cannot be due to heat intercepted by oxygen and ozone.

The change of the lapse rate with height deserves careful consideration, and it would be interesting to know how it varies with latitude along lines of longitude passing over continental and oceanic areas respectively. Fig. 54 gives the mean lapse rate for Europe as illustrated by the mean figures in Table IX, but it is probable that the effective lapse rate below the tropopause is more in accordance with the curve shown in Fig. 55.

The peculiar distribution of temperature with height cannot be entirely due to the sun's radiations of one kind or other being intercepted only by such gases as oxygen, ozone, water vapour, etc. more or less throughout the whole height of the atmosphere either on their way to the earth's surface or as they are again radiated from the earth's surface, or by clouds, mist or fog. Indeed the upper limits of the atmosphere must be pierced by all the heating rays the earth receives from the sun, and by the same amount of heat again as it is again radiated into space, whilst the lower portions of the atmosphere receive a considerable supply of heat owing to convection currents rising from the earth's warm land and water surfaces, and from heated clouds, etc.

When the upper side of an air stratum is heated by light and heat rays, the heating can take place only owing to the presence of oxygen, ozone, carbonic acid gas, water vapour, or occasionally the presence of dust. Now the gases mentioned absorb only rays of a certain wavelength, and when such rays are all filtered out no further heating can take place at lower levels except by conduction, and the downward movement of heat in this way is rather slow. But the heating by heat waves of the upper atmosphere in low latitudes would not account for the heating in high latitudes where the sea-level pressure is low even during the long, dark polar winters. Such heating by the sun's heat and light rays of the gases of the atmosphere in low latitudes in its upper portions makes the problem of the winds more difficult still; for the heating is above where high pressures exist.

When a ray of sunlight is passed through a prism of transparent rock salt it is spread out into a band showing the colours of the rainbow, red being at one end and violet at the other, and if these colours be reunited by reflection from a curved polished surface the effect is to reproduce the original sunlight. But the rays that are seen to form the colours of the band are not the only ones that pass through the prism ; for outside the coloured band at both ends other invisible rays are present. This is easily proved, for when a thermometer bulb is placed just beyond the red end of the coloured band it will show a rise of temperature, indicating that invisible heat rays are passing through the prism. Glass largely absorbs these heat rays, as do certain gases which the atmosphere contains, each gas being opaque, or nearly so, to particular rays ; but rock salt is very transparent to them. Certain rays only can be absorbed by oxygen and ozone, others by water vapour, and others by carbonic acid gas.

When the air is moist and there is a clear sky, radiation from the earth chills the surface and this cold surface chills the air in contact with it until the temperature falls below the dewpoint and dew and fog are formed. The particles of water in the air also lose heat by radiation, become cooled, water vapour in the air around condenses upon them and increases the density of the fog. This condition is common in winter ; it occurs, however, at all times of the year in fine weather when air saturated with moisture is cooled. Thus whenever an anticyclone covers England at a time when the air is moist and drifts north from the Atlantic, fog forms. On the other hand, when the air is dry and comes from the continent the atmosphere remains clear, and in winter is frosty.

The upper level of the troposphere—the tropopause—is the height at which the temperature gradients of the troposphere and stratosphere cross each other. There is ample proof that the air of the upper atmosphere, even over the poles, is warm, and often very warm in the polar winters when it is in the dark and receives no direct radiations from the sun. Indeed at the " horse latitudes " the atmosphere as a whole must be cooler than it is over the poles, for even if the tropopause is higher and colder in low latitudes than in high ones, the lower atmosphere there is very warm.

Valuable information concerning the temperature of the upper atmosphere has been obtained by a study of meteors. These strike the attenuated air at very high speeds, and the temperature of the vaporised meteor is raised to

incandescence. The air the meteors strike must have a temperature of about 300° C. Abs. Prof. Lindemann has studied this question closely, and published some of the interesting and valuable conclusions he has come to.

We will consider the case of a typical meteor, which is as bright as a first-magnitude star, and is about the size of a small shot (1·15 millimetres diameter). It appears at a height of about 100 kilometres and disappears at a height of about 80 km., after travelling 60 km. in 1·5 seconds. Such a meteor after striking the atmosphere collects in its front a cap of dense air heated by compression, and this high-temperature air melts and volatilises the meteor and the mass becomes incandescent. When this occurs the meteor becomes immensely larger, and, therefore, visible to the naked eye, and it is only when this volatilisation produces incandescence to an appreciable extent that the meteor does become visible, for however hot a particle the size of a meteor becomes, unless it is volatilised and becomes incandescent, it could not be seen at a distance of 100 kilometres. It is thus the light radiation emitted when the meteor heats, evaporates and forms a mass of dense air in front that makes it become visible. For the air in front of the meteor to volatilise it, the air it strikes, as already stated, must have an initial temperature of about 300° C. Abs. This conclusion, stated by Lindemann in 1926, supports the present author's conclusions published in 1918, that the upper portion of the stratosphere must be very warm indeed. However, it is not only a general high temperature in the upper atmosphere that is required to produce our primary winds. The temperature of the upper air over the poles must also be much greater than over the equator.

Numerous references have been made to the possibility of the upper atmosphere being heated at considerable heights over high latitudes by matter thrown out by the sun. To cause such material radiations to reach the magnetic poles, they would have to be electrified, so that they would be deflected by the earth's magnetic field towards the poles. As this matter has a bearing upon the theory of the winds, the magnetic field of the earth can conveniently be considered here.

The earth is a great magnet, and it is on this account that the compass needle points to the magnetic poles. These magnetic poles are some distance from the North and South geographical poles of the earth. Like every other magnet, the earth produces a magnetic field in the surrounding space, and wherever the compass is placed in

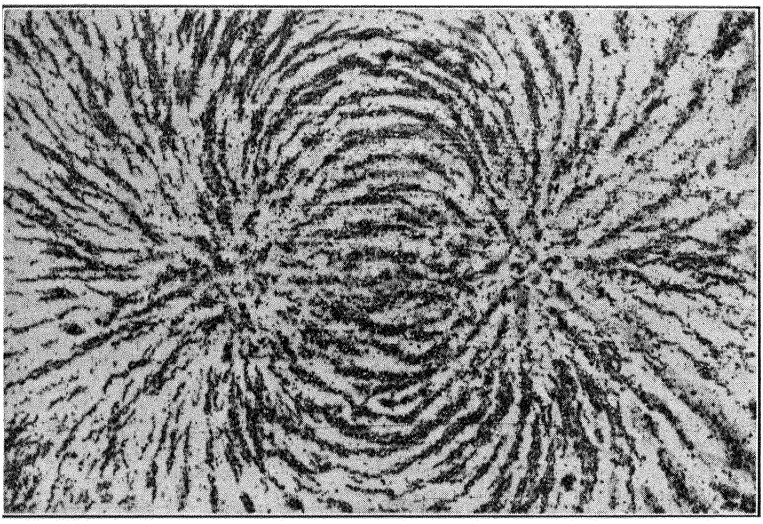


Fig. 56.—Magnetic Lines of Force shown by Iron Filings in Magnetic Field.

this field the finger places itself along the lines of magnetic force and points to the magnetic poles, not to the poles of the earth's geographical axis. The magnetic field surrounding the earth is of exactly the same nature as that surrounding the poles of a common horseshoe or bar magnet. If we place a sheet of paper between the poles of a horseshoe magnet, dust some iron filings on to the paper, and gently tap it, the filings will collect along the lines of force. Fig. 56 shows the pattern produced, and the finger of a small compass placed on the paper will set itself parallel with these lines or ridges of iron filings.

It must not be supposed that there is actually a "line" of force where the filings collect to form continuous ridges reaching from pole to pole of the magnet ; for if the paper be marked to show where the ridges are, and the filings be again dusted on the paper, they will again form ridges, parallel with the old ones but not necessarily in the same places.

We can imagine the whole space between the poles of the magnet as being filled with these lines of force, and the greater the strength of the magnet the more such lines we can imagine there are. Imagine now that we have a very small electrified particle, and drop it so that it will fall somewhere between the two poles of the magnet. When it reaches the magnetic field, instead of continuing to fall vertically, it will turn aside and slide in the direction of these imaginary lines of force to the nearest magnetic pole. Electrified particles shot out by the sun act in the same way, and those which do not strike the lines at right angles will slide approximately down the earth's lines of force and reach the atmosphere at or near one of the magnetic poles. It is such electrified particles striking the earth's atmosphere that are regarded as the cause of the Aurora Borealis and Aurora Australis. These particles or corpuscles move at very great speeds, but how they heat as well as electrify the air over high latitudes, even during the long cold nights of winter, is not quite clear.

CHAPTER IX.

THEORY OF THE WINDS—PERMANENT WINDS.

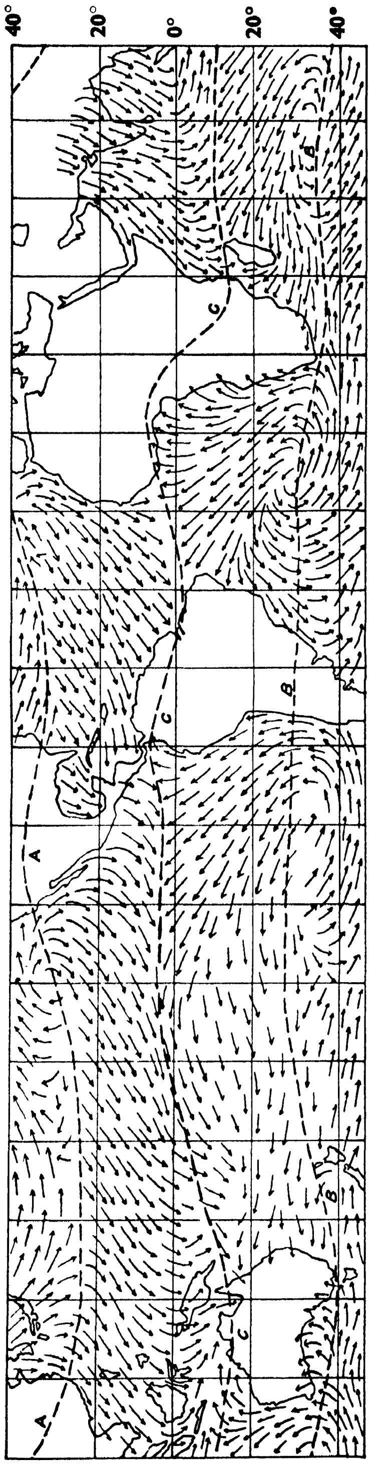
It is generally agreed that the winds of the earth can, with advantage, be divided into three groups:—

(1) Permanent but variable winds which dominate large areas.
(2) Periodic winds which blow with more or less regularity during certain seasons of the year.
(3) Variable winds which mar the regularity of those of the first two groups.

The permanent winds are the most marked and interesting, for they are mainly responsible for the general air circulation of the globe. They are evidently the winds that would almost dominate the globe in the absence of continental land masses, and especially elevated land areas such as high plateaux and mountain ranges. Our knowledge of the lower winds of this kind is fairly complete, except in the polar regions; but there are other upper winds, forming return currents, belonging to the same category, which are not so well known. Information concerning the upper permanent winds has been obtained chiefly by observing the movements of the upper clouds. However, high clouds, such as cirrus (also known as "mares' tails"), are mainly produced when variable wind and weather conditions are developing, and on that account cannot always be relied upon to give precise information concerning the general circulation. Lofty isolated mountains, such as Teneriff, give some information. Balloons of various kinds have also proved useful. They are so charged with gas in relation to their weight that they rise to high levels, and float in the upper winds for long distances before they fall.

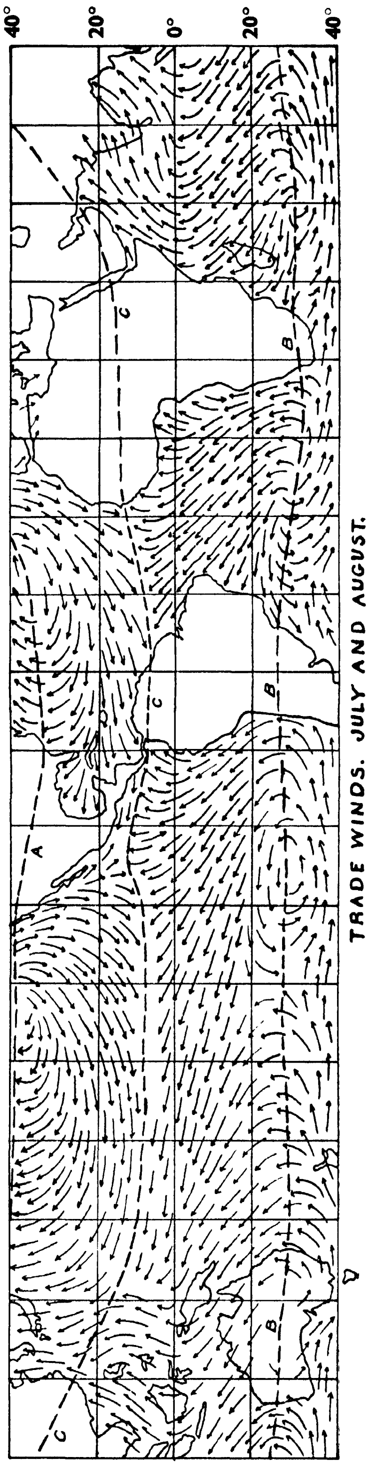
It will be convenient, in the first place, to show as nearly as may be, the courses of the permanent winds in the troposphere, omitting for the time being all reference to periodic and variable air movements due to local causes.

The wind provinces of the globe can be divided into three great areas; the first, which is shown between the



TRADE WINDS. JAN. AND FEB.

Fig. 57.



TRADE WINDS. JULY AND AUGUST.

Fig. 58.

lines *A* and *B* in Figs. 57 and 58, covers a considerable area on each side of the equator between the "horse latitudes." Here the lower general air movement is from

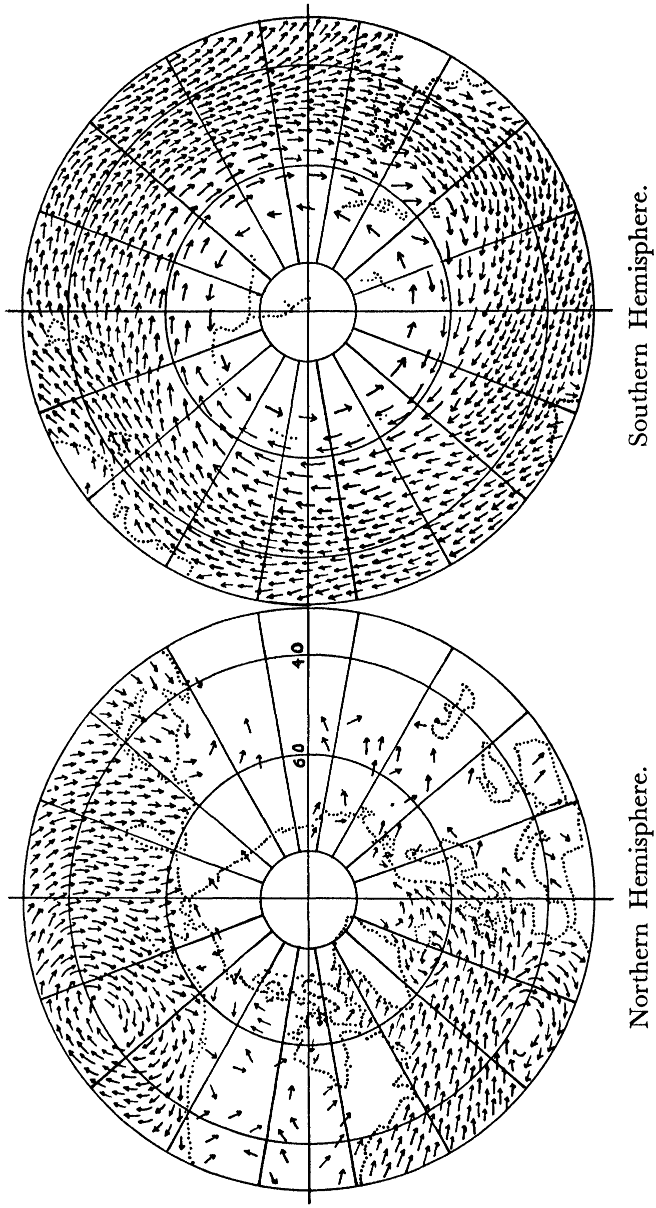
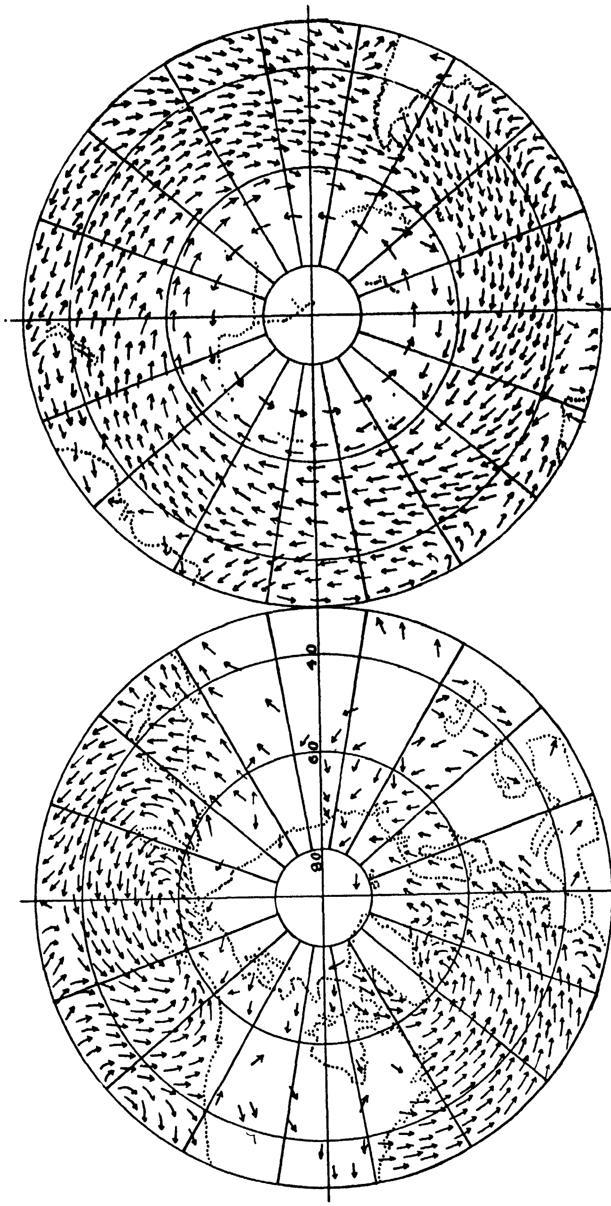


Fig. 59.—Winds of Middle and High Latitudes, January.

the north-east and south-east towards the equator. Fig. 57 shows the January and February conditions, and Fig. 58 the July and August conditions. The central dotted line *C* is over the low-pressure area of the easterly but somewhat

variable winds, the narrow belt being called the "doldrums." The two outside dotted lines *A* and *B* are over the high-pressure belts of the "horse latitudes." Along these two belts we



Northern Hemisphere. Southern Hemisphere.

Fig. 60.—Winds of Middle and High Latitudes, July.

have several anti-cyclones caused by varying local conditions. The whole central province between *A* and *B*, which is that of the trade winds, moves bodily north and south with the seasons, the greatest variation occurring over the Indian

Ocean, as the result of the development of the Indian wet Monsoon.

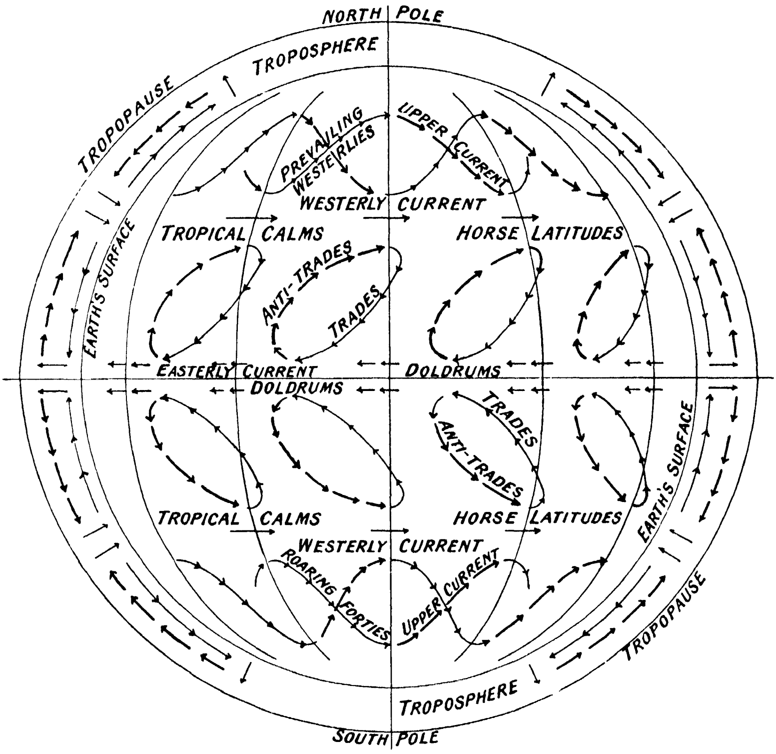
The other two wind provinces are shown in Figs. 59 and 60 and extend from the " horse latitudes " to the poles, Fig. 59 showing the January conditions and Fig. 60 the July conditions. In the charts the differences between the Southern Hemisphere and Northern Hemisphere circulations are seen at a glance, for unlike in the Northern area, a great cyclone dominates the South polar area during both winter and summer. In the Northern Hemisphere the continents and mountain ranges are responsible for the breaking up of the circulation into two somewhat persistent cyclonic areas, one over the North Pacific and the other over the North Atlantic.

The charts of the winds that have been given show only the lower air movements ; but these winds could not continue to blow if there were not upper winds—re-entrant currents—to return the air to the starting points. Although a considerable amount of information has been obtained concerning the upper winds, it has not been possible to chart them for the whole earth with certainty, especially in such instances as the Indian Monsoon area, and where great mountain ranges, such as the Himalayas, interfere with their flow. However, their directions are sufficiently well known in the Southern Hemisphere to enable us to illustrate their main characteristics when local movements are excluded. Fig. 61 illustrates the nature of the circulation in the troposphere as nearly as can be made out from the evidence at hand, the assumption being that there are no mountain ranges, plateaux or great land areas to produce local effects.

At the equator we have the narrow belt known as the " doldrums." This region is shown as being actually over the equator ; but its true mean position is some degrees to the north, the displacement being due to the disparity between the land areas in the Northern and Southern Hemispheres. It is farthest north in the northern summer and farthest south in the southern summer. Its position is at the meeting of the northern and southern trades, where the air rises, a region of light irregular winds, low pressures, heavy rainfall and occasional thunderstorms. The skies are often filled with cumulus and other clouds that show the existence of strong ascending currents. Above the " doldrums " a current of air from the east blows throughout the year, having an increasing velocity with height. At great altitudes, 10 to 15 kilometres and possibly higher, the velocity

of this wind is about 80 miles per hour. At the equator the tropopause reaches a height of 17 kilometres, so this wind of hurricane force is well within it. Whether it extends into the stratosphere other than by viscous drag is not certain. Of course, it may originate in the stratosphere. Its presence has not been satisfactorily accounted for.

This easterly wind, however, is a movement which could



(Upper Winds are indicated by Thicker Arrows.)

Fig. 61.—Theoretical Atmospheric Circulation in Absence of Continents and Mountain Ranges.

be produced by the entry into the earth's atmosphere of material particles from space that did not partake of the angular velocity of the atmosphere. Such particles if they mingled with the air would impart a movement to it which would be recognised as an easterly wind. Still there is no evidence that sufficient matter, coming from space, reaches the earth to produce this wind and result in its extension to middle latitudes.

On each side of the " doldrums " we have the " trades "

and "anti-trades." The word "trade" comes from the verb "tread," and originally meant a "beaten path." Hence "trade" and "traffic." The trade winds are so called since they blow along a regular course over the seas; but their direction is much disturbed by land areas. Table XI shows that they cover about half the globe, and indicates the distance they march north and south with the seasons. Between these latitude limits is the low-pressure trough of the "doldrums," towards which the trades blow from both sides in accordance with Buys Ballot's law. On the north side of the equator the flow is from the north-east, and on the south side from the south-east. These are the best-known permanent winds, and may be said to originate in each hemisphere in the high-pressure belts of the "horse latitudes." They are remarkable for their steadiness, both as regards direction and velocity, particularly over the oceans. It would appear that the trade winds are strongest during the winter and weakest during the summer, and that the south-east trades are about one-third stronger than the north-east ones. Over the Indian Ocean they are much interfered with by the Indian Monsoon.

TABLE XI.

Trade Wind Data.

Permanent Wind.	Latitude Limit.	Winter.	Summer.
N.E. Trades .	Upper	20° N.	35° N.
,, .	Lower	3° N.	11° N.
Doldrums . .	Upper	3° N.	11° N.
,, . .	Lower	0° N.	3° N.
S.E. Trades .	Upper	0° N.	3° N.
,, .	Lower	25° S.	25° S.

This inflow of air from both sides causes the air of the "doldrums" to rise and spread on each side over the trades. These upper winds are the "anti-trades," and they blow from the south-west in the Northern Hemisphere, and from the north-west in the Southern Hemisphere. They are shown by the thicker arrows of the dotted lines in Fig. 61.

Table XII shows the depth and thickness of the trades at several places.

TABLE XII.

Trade Wind Data.

Locality.	Latitude.	Thickness.
Cuba . . .	22° N.	11,500 feet.
Hawaii . . .	19° 30′ N.	10,000 "
Jamaica . . .	17° N.	21,000 "
Trinidad . . .	12° N.	26,000 "

We thus see that the trade winds are thickest near the "doldrums" and thinnest near the "horse latitudes."

That the trades and anti-trades blow in opposite directions is a very interesting fact, for the pressure gradient between the "doldrums" and the "horse latitudes" must be reversed at high levels to make the anti-trades obey Buys Ballot's law. If the pressure gradients were not reversed in this manner, but remained at high levels as they are at low levels, the anti-trades would be easterly not westerly winds. The high-temperature air rises in the "doldrums," and presses against the upper, cold air of the troposphere, which accordingly moves in northerly and southerly directions from the equator, in accordance with the demands of the density gradient.

In Fig. 68, which is a hypothetical section of the atmosphere from the equator to the poles, showing the mean annual isotherms, if the pressure gradients in the troposphere over the trade winds be calculated, it will be found that they place the pressure reversal at rather a low level. This may be caused by a small error in the height at which the tropopause is placed.

Fig. 68 is a reproduction, with slight alterations, of a diagram drawn by the present author, and published in a paper "Rain, Wind and Cyclones," which appeared in the *Philosophical Magazine* for March, 1918 (p. 233).

The great area between the "horse latitudes" we have been dealing with comprises about half the area of the globe, and the air movements within it are remarkably constant in direction and force. They closely obey the march of the sun, and therefore also of the seasons. On this account it would appear that the driving force they obey is mainly if not completely due to the heating of the troposphere by the sun's light and heat rays, and apparently they are not very much influenced by anything that is taking place in

the stratosphere. This, as we shall see, probably also applies in some measure to the origin of tornadoes, tropical hurricanes, sea and land breezes, monsoons, etc. However, to what extent the trade winds are influenced by irregularities of the "solar constant" is a matter for future research.

From what has been stated it will be seen that the province of the trade winds does not owe its air movements to density gradients arranged like those in cyclones ; for in a cyclone the density gradients always slope towards the low-pressure centre, as will be seen in Fig. 52, whereas in the case of the trade winds the density gradient reverses at moderately high levels and gives rise to the anticyclonic anti-trades.

Both north and south of the trade winds we have the "horse latitudes." Here the anti-trades come down and feed the trade winds and to some extent there is here an interchange of air between low and middle latitudes. These two comparatively wide, calm, high-pressure belts, are not very clearly defined, but are very important climatic features. Apparently there is very little vertical movement over their centres. The winds on their edges, however, are descending. The bands are much broken into by comparatively high- and comparatively low-pressure areas, which owe their presence to the existence of land masses and oceans, and to the march of the sun north and south of the equator. Indeed as we come to consider areas outside the region of the permanent equatorial winds, the effects of the seasons become more and more marked. The circulation of the air in "horse latitudes" favours a small precipitation ; but this matter will not be treated until we come to deal with the actual circulation of the lower atmosphere as affected by land and water, summer and winter, and the effects produced in the troposphere by temperature changes in the stratosphere.

The two high latitude areas in which blow the prevalent south-westerly winds of the Northern Hemisphere, and the "roaring forties" of the Southern Hemisphere, are regions of great interest, and have proved very difficult to deal with from the point of view of theory. The usual plan has been to regard the area where the trade winds blow as being under the influence of thermal forces, and the two outer low-pressure areas as being subject to dynamical influences ; but we are not told what these dynamical influences are. All the known facts favour the view that the trade winds are caused by thermal effects largely in the troposphere ; but it is

equally plain that such thermal forces do not exist in middle latitudes in the troposphere in a way which could account for the prevalent winds and the very deep cyclones that often occur there ; and as it seems that the only forces which act with appreciable effect upon the atmosphere as a whole are those resulting from variations of density produced by differential heating, the view here taken is that the peculiar nature of the circulation of the air in middle and high latitudes is due to the high temperature of the stratosphere over high latitudes, especially in the winter. This theory will be considered in some detail later. Here only the form of the circulation in the troposphere and the temperature conditions therein, will be dealt with.

In the Northern Hemisphere, north of the "horse latitudes," the water surface is so broken up by continental land areas and high mountain ranges that the wind conditions shown in Fig 61 actually apply only to the portions occupied by the oceans. Though this is the case in the north, the conditions are quite different in the south, for there the continents taper off in a southern direction, and the Antarctic Continent is situated right in the centre of the great southern cyclone. In these two great areas the dominant winds can be regarded as circulating as shown in Fig. 61, the lower winds being represented by the full lines and the upper ones by broken lines. Unlike the troposphere circulation in the area of the trade winds, both the upper and the lower winds in middle latitudes are mainly westerly ones, the low-pressure centres of the cyclones extending to the top of and above the troposphere. Under such pressure conditions Buys Ballot's law does not demand that the upper and the lower winds shall blow in opposite directions, as is the case with the trade winds.

Another marked difference from the trades is that the prevailing westerlies and the "roaring forties" are very variable in strength. We read that in 1879 the "Normancourt," which in the opinion of many good judges was the most beautiful of the China clippers, being more like a yacht than a trading vessel, had made for some ten years some very fine passages. However, in 1879, having run from the Lizard to the equator in 23 days, it took 85 days to reach Sydney, owing to the absence of the usual strong westerly winds of the "roaring forties." It seems to be more than a chance coincidence that December 1879 was one of the coldest of which there is any record, Europe experiencing extremely low temperatures owing to the weakness of the prevailing westerlies of the Atlantic. It is a fact however

that outside the trade wind areas, although the air movements are generally as shown in Fig. 61, the winds show great variations in their strength and direction.

In some old charts purporting to show how the general winds blow, we see "polar calms" written over the areas within the Arctic and Antarctic Circles. At times there certainly are calms there; but as a rule there are numerous deep cyclones and furious winds there. Indeed, even during the long dark polar nights, great cyclones thousands of miles in diameter develop and persist over the polar areas for weeks together, and we often find several cyclones in action there at one time. In the North polar area the low mean pressures found are due to the presence of many such cyclones, generally sweeping over the Northern Atlantic and Northern Pacific from west to east.

In both the Arctic and Antarctic Regions, in the neighbourhood of the Poles in winter, a very cold layer of air often forms of no great thickness, and this cold air spreads outwards, forcing itself under the warm winds coming from lower latitudes. This is a marked feature of the Antarctic Continent, the winds descending from the high ice-covered plateaux and warming as they come down. The regions where these winds meet the westerlies are often at the edge of the pack ice, which circulates round the Antarctic Continent, and also lies off the eastern side of Greenland.

In another chapter the question of polar climates will be considered, and we shall then see that the pressure and temperature variations outside the "horse latitudes" generally grow more and more pronounced as we move from low to high latitudes.

In a future chapter we shall also deal in some detail with pressure conditions in the Arctic regions. This can now be done owing to the publication by the Meteorological Office of daily charts covering a large portion of the Northern Hemisphere north of the "horse latitudes."

So far the winds of the troposphere have been considered without any detailed reference to the stratosphere; but the circulations in both the upper and lower atmosphere affect each other very considerably, although the transfer of air from one to the other is probably small.

G. M. Dobson obtained, by means of sounding balloons on Salisbury Plain, much information concerning the velocity of the wind in the lower portion of the stratosphere as compared with that in the upper troposphere. His results are summarised in Fig. 62. Here distances and mean wind velocities above and below the tropopause are shown

graphically. The first group of observations, represented by the curve *A*, includes all observations in which the wind velocity was small. These occasions of relatively light wind show no great change of velocity on passing from troposphere into stratosphere. When the winds were stronger the case was different. Curve *B* takes into consideration occasions on which the velocity was moderate—these results show a

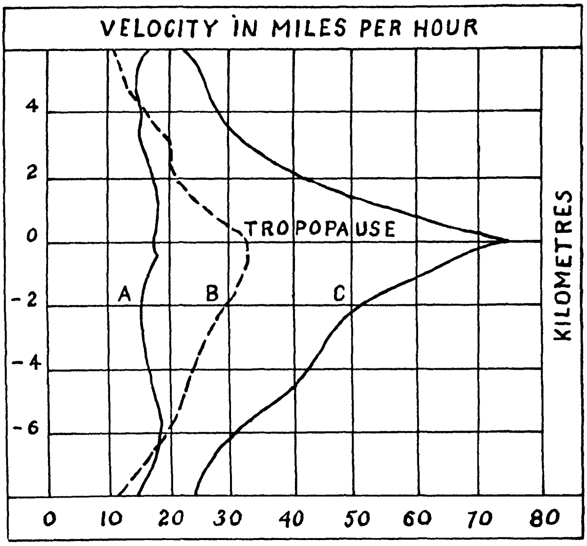


Fig. 62.—Winds Near Tropopause in Cyclones.

decided maximum velocity at the level of the tropopause. The effect is much more conspicuously shown by curve *C*, which was drawn for strong winds. Here the abrupt transition from the condition of increasing velocity with height in the troposphere to one of decreasing velocity with height in the stratosphere is very marked.

The air movements in the lower stratosphere would appear to be caused by the viscous drag of the movements below the tropopause, the resulting outward whirl in the stratosphere obtaining its supply of air from above, which air is warmed by adiabatic compression as it descends, and thus depresses the tropopause. Indeed the higher temperature of the air column at the centres of cyclones is due largely to the rise of temperature above the tropopause when it is low and the troposphere correspondingly thin.

The relations between latitude, pressures and temperatures may be illustrated graphically with advantage by plotting the temperatures and pressures which occur along certain

meridians, the abscissae being latitude and the ordinates temperatures or pressures.

Fig. 63 shows how the annual mean temperature varies along the two meridians 15° West longitude and 75° East longitude, corrections being made so as to reduce the figures to sea-level. The curve *A* is along 15° W. longitude and, with the exception of that portion which passes over the extreme westerly side of Africa, is wholly over water ; whilst the curve *B* passes across Siberia, Central Asia and India, and then southwards over the Indian Ocean. Both these curves show very considerable temperature gradients from the equatorial towards the polar regions. The mean temperatures along both meridians do not differ greatly in the Southern Hemisphere, but in the Northern Hemisphere the temperature differences shown are higher but somewhat irregular.

Figs. 64 and 65 are drawn to illustrate how the temperatures along the same two meridians vary from winter to summer. The dotted lines are for the purpose of making the difference of temperature between summer and winter easy to judge. In the Southern Hemisphere the difference between the temperatures of the two longitudes in January is not great ; but in the Northern Hemisphere 75° East longitude is much colder than is 15° West longitude in January. However, in July both longitudes are seen to be warmer in the Northern than in the Southern Hemisphere.

Fig. 66 shows the variations of atmospheric pressure along the meridian 100° E. for January and July. The pressure variations are here seen to be much greater between summer and winter in the Northern Hemisphere than they are in the Southern. During both January and July the high-pressure ridge of the southern "horse latitudes" persists, and the winds blow from it the year round. However, during July the pressure ridge of the northern "horse latitudes" gives place to low pressures, and there is then a continuous pressure gradient from 30° S. latitude to 40° N. latitude, and this gives rise to the Indian wet Monsoon.

In Figs. 64, 65 and 66 the arrow heads on the curves of pressures and temperatures show the wind directions. It will be noticed in Figs. 64 and 65 that the fall of temperature is continuous from the equator southwards, but that in spite of this the winds blow in opposite directions from a point about 30° S. latitude, the winds of middle latitudes taking the direction of a falling temperature gradient. A similar state of affairs exists in the Northern Hemisphere during January ; but in July, along the meridian 75° E., the wind blows in accordance with the requirements of the

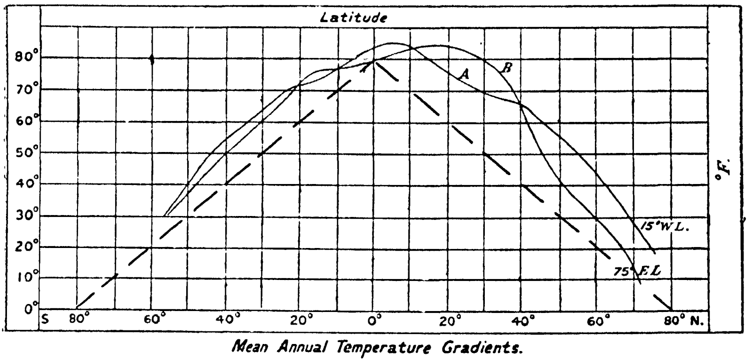


Fig. 63.

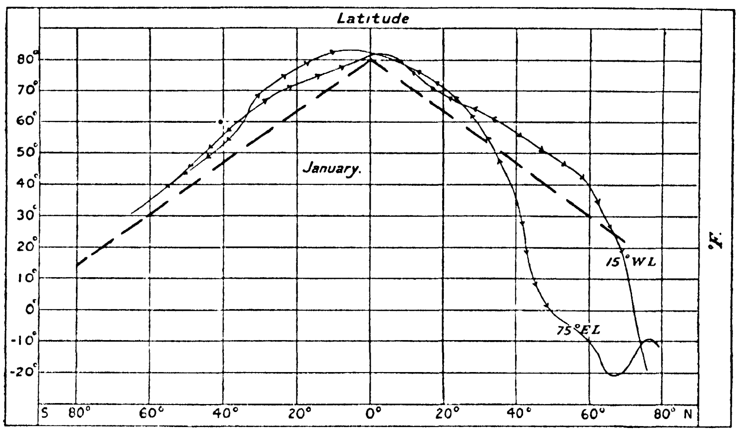


Fig. 64.

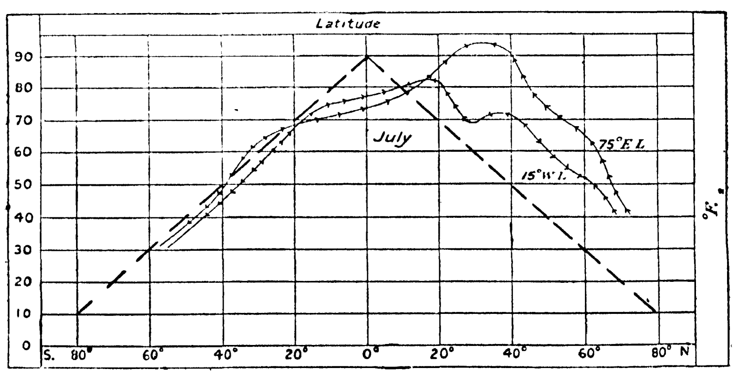


Fig. 65.

Figs. 63, 64, 65.—Variation of Temperature with Latitude along Meridians 15° W. and 75° E.

surface temperature gradient. In the equatorial regions between 30° S. latitude and 30° N. latitude the winds everywhere follow the temperature gradients. We see from this that in middle latitudes the winds generally do not obey surface temperature gradients, but that in equatorial regions they do.

Although even at the earth's surface there is a very fair agreement between the directions of the winds and barometric pressure gradients, it must be borne in mind that the direction of the surface winds is varied greatly by local features and local irregularities of temperature, whereas the barometer measures the weight of the whole atmosphere above the particular spot, and many differences of air temperature

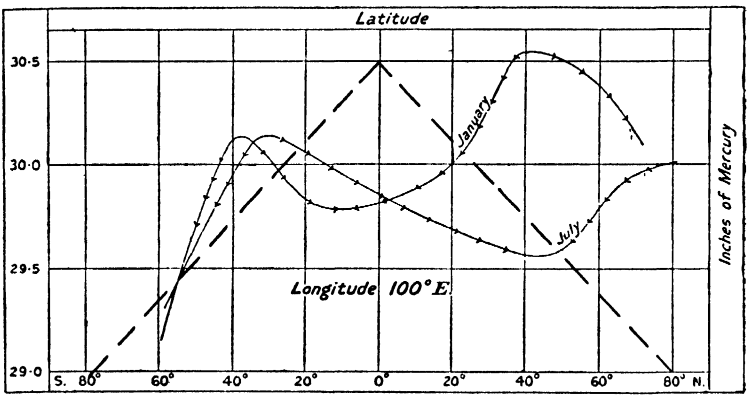


Fig. 66.—Variation of Pressure with Latitude along Meridian 100° E.

involve so thin a stratum of air as scarcely to affect the pressure gradient.

The pressures over the Atlantic along longitude 20° W. are shown in Fig. 67. Here, except in the extreme north, the pressure distribution is much the same in both hemispheres, but the pressures are higher in July than in January. This arises from the fact that the land areas in the summer are more heated than the water areas, and as the greater part of the land is in the Northern Hemisphere, during the summer there the air is to some extent transferred from the land to the water areas.

The temperature and pressure curves that have been illustrated show clearly that the great land areas in the Northern Hemisphere have a great disturbing effect upon the atmospheric circulation in that hemisphere. In the Southern Hemisphere the curves show much more simple conditions, due no doubt to the tapering of the southern

continents and the concentric position with respect to the earth's axis of the Antarctic Continent.

If the winds of the Southern Hemisphere followed the temperature gradient of the troposphere, we should expect to find, in middle and high latitudes, an upper current from the north-east and an under current from the south-east. Buys Ballot's law would then demand a high pressure over the South polar area. Similar reasoning would apply to the Northern Hemisphere, but the large land areas there would prevent the formation of a symmetrical anticyclone. However, anticyclones generally are prevented from forming over the polar areas by the great heat, and consequently low density, of the stratosphere.

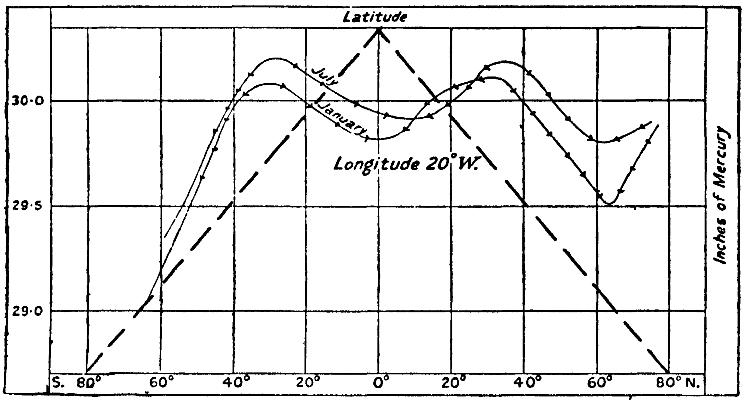


Fig. 67.—Variation of Pressure with Latitude along Meridian 20° W.

We thus have, generally speaking, in the Northern Hemisphere, the cyclone broken up into two well-marked low-pressure areas, one over the North Atlantic, and the other over the North Pacific. These are generally separated by a moderate ridge of high pressure extending from Eastern Siberia across the Arctic Ocean to Alaska and adjacent portions of Canada. Over North America, Europe and Asia the great differences of temperature between winter and summer due to the presence of mountain ranges and high plateaux, produce alternating cyclonic and anticyclonic conditions of a secondary character.

The problem of the distribution of temperature, and of the air movements, in the stratosphere, is a difficult one to deal with, so few registering balloons having penetrated it more than a few kilometres. However, by using the indirect methods of reasoning at our disposal, as well as such direct

methods as are available, a tolerably good idea of the phenomena presented by the upper atmosphere can be formed.

A tentative diagram of the temperature phenomena of the atmosphere from the equator to the poles is shown in Fig. 68. It is intended to illustrate approximately the mean annual conditions. But the atmosphere is subject to very great temporary changes, and there are constant differences between the conditions in the Northern and Southern Hemispheres respectively, due to geographical differences.

Hitherto, as previously stated, no soundings have been made which reveal satisfactorily how the vertical and horizontal temperature gradients in the stratosphere and troposphere vary with longitude and latitude. Such records as we have, favour the idea that the troposphere is thicker in low latitudes than in high ones, and that in the troposphere, although the surface temperature gradients nearly everywhere favour surface winds blowing towards the equator, the winds only do so in low latitudes. Therefore there must be temperature gradients in the stratosphere which overpower the gradients at the earth's surface and produce the low pressures which exist in the stratosphere in middle latitudes, pressures which favour surface winds towards the poles. As a rule this middle latitude low pressure resulting from the high temperature conditions in the stratosphere is sufficiently strong to produce cyclonic conditions there.

In high latitudes, where the tropopause is low, its temperature is comparatively high, as will be seen from Fig. 68, and this results in the air of the stratosphere having a higher temperature than it has in low latitudes.

Europe is not a satisfactory area for showing the effects of the temperature of the atmosphere at various latitudes on the winds, for it is a large land area. For example, the stations the mean atmospheric temperatures above which are given in Table IX, although extending from latitude 45° in Italy to 68° in Sweden, do not furnish a satisfactory illustration of the changes of temperature and pressure with change of latitude ; for the differences of pressure, due to the seasons, between Abisco and Pavia are small.

Before dealing with the diagram, Fig. 68, it would be well to note how tenuous the air is at great heights. Fig. 69 has been drawn to show this. Here the abscissae are pressures in millibars and the ordinates kilometres in height. It will be seen that a little more than one-quarter of the atmosphere lies above ten kilometres. Differences of pressure amounting to more than 100 millibars often exist in the

Arctic regions between cyclonic and anticyclonic areas, and if we regard the cyclone as having a pressure of 50 millibars below the mean, the diagram shows that all the

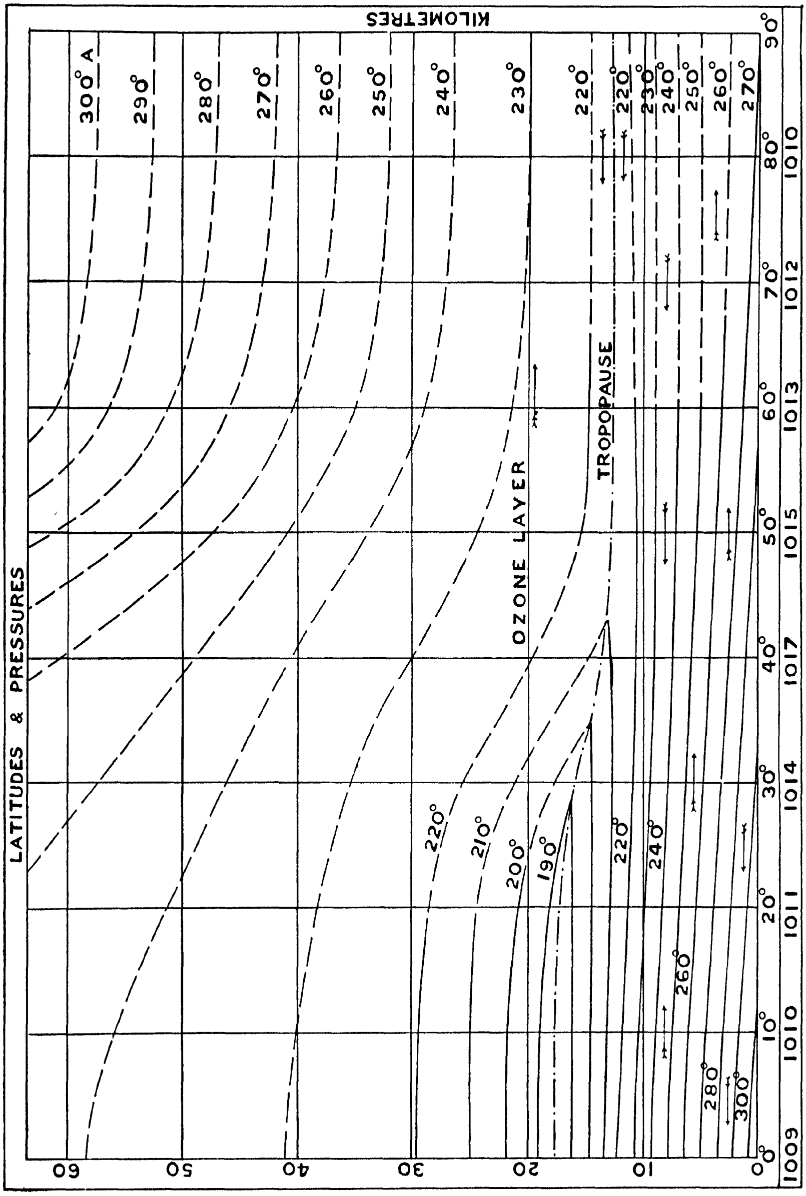


Fig. 68.—Theoretical Vertical Section of Mean Annual Isotherms from Equator to Pole.

air above 21 kilometres would have to be removed to produce this fall of pressure. It is these great pressure ranges which make it difficult to accept current theories concerning pressure changes.

For example, on February 20, 1930, a cyclone whose centre was over Spitzbergen showed a fall of pressure of 51 millibars below the mean. This would require the removal from the centre of the cyclone of as much air as normally exists above a height of about 21 kilometres. This great reduction of pressure occurred in the depth of the sunless Arctic winter. No pilot balloon has ever sounded

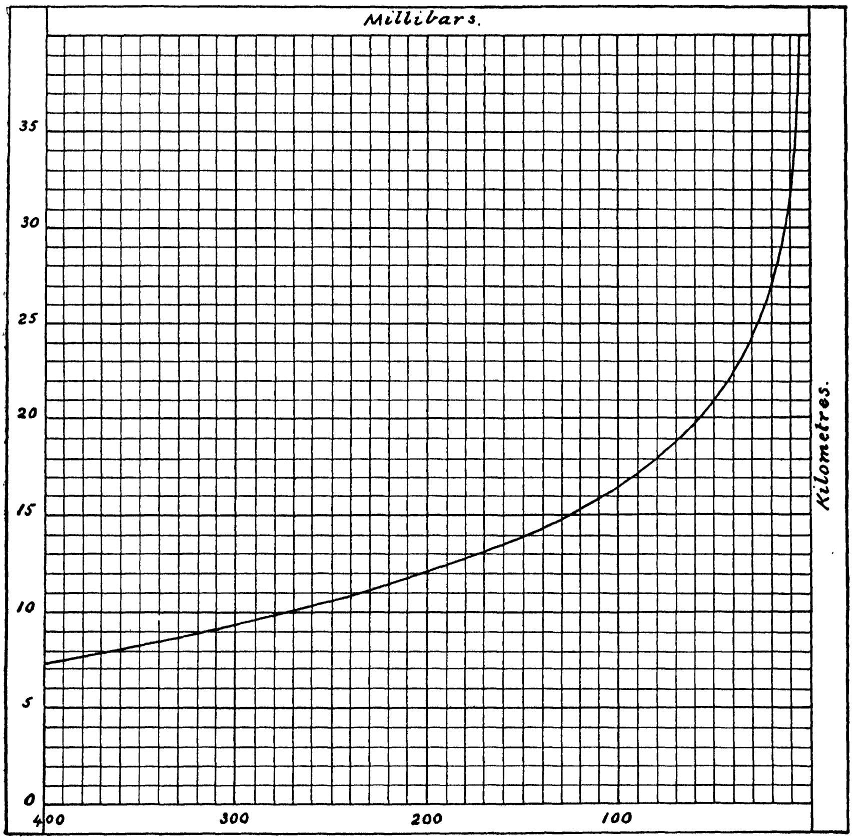


Fig. 69.—Showing Decrease of Pressure with Height.

such a cyclone, but it is clear that the stratosphere and upper troposphere must have had their temperatures raised locally very considerably to produce such an effect.

In Fig. 68 the ordinates are heights in kilometres and the abscissae are latitudes. As in Table IX, temperatures are shown to be high at high levels over the poles, and also at sea-level near the equator, whilst the lowest temperatures occur high up above the equator and low down near the poles. Above 60 kilometres the air remains warm up to the confines of the atmosphere, for meteors become

incandescent at heights of 150 to 80 km., and they disappear at any height above ground level. At such great elevations the atmosphere is very attenuated, and must be heated even over the poles by radiation from the sun other than light and heat rays, even during the dark nights of the Arctic and Antarctic winters.

Between the "horse latitudes" and the Antarctic Continent the barometer normally falls at least 35 millibars, about one inch of mercury, and this difference of pressure generally persists throughout the year. In the Northern Hemisphere the fall of pressure in high latitudes is less, and more irregular. The existence of this low pressure over the Arctic Sea and Antarctic Continent can only be caused as already explained by the heating of the upper atmosphere from above.

In Fig. 68 the probable varying height of the isotherms from the equator to the poles is shown. It may be that the ground pressure conditions, shown in millibars, which are regarded as those corresponding to the latitudes, are not exactly such as the temperatures shown by the isobars warrant. Comparatively small differences in the positions of the isothermal lines in the lower troposphere make considerable differences in the densities and therefore the ground barometric pressures. However, the fact must not be lost sight of that the high temperatures of the high-level isotherms which often obtain during the Arctic and Antarctic winters cannot be due to troposphere heating. The heating must be in the stratosphere.

The heated air above the polar regions, indicated in Fig. 68, cannot remain as a dome above the general level, and it flows off in all directions from the heated centre, forming a low-pressure area, which extends down to the sea or land surface. Above the tropopause, and within a few kilometres of it, as shown in Fig. 62, the viscous drag of the upper winds of the troposphere induces an outward flow in the stratosphere. We thus have an outward flow of the air both at high and low levels in the stratosphere and an inward spiral movement in the stratosphere at about the ozone level. The outward moving air immediately above the tropopause would draw down air from above which, heating adiabatically, would rise in temperature and depress the tropopause.

The circulation just described would seem to be what happens in all but very small cyclones.

The nature of the circulation over the tropics has been described when explaining Fig. 61.

CHAPTER X.

THEORY OF THE WINDS—VARIABLE AND PERIODIC WINDS.

IT has been pointed out that the permanent winds are most regular in their action between the northern and southern "horse latitudes," where they are known as the "trade winds" and "anti-trades." Outside this area the prevalent winds blow more irregularly; but they are sufficiently constant in character to be considered as dominant. In the Southern Hemisphere they take the form of an immense cyclone of a permanent character, with the winds of which drift secondary cyclones. In the Northern Hemisphere, owing to the presence of great land masses and mountain ranges, the primary cyclone is broken up and has two pronounced centres of action, one over the North Atlantic and the other over the North Pacific, and with the winds of this primary cyclone, and its two centres of low pressure, drift numerous secondary cyclones.

Outside the "horse latitudes" the cyclonic winds are irregular in force and direction and vary both with the seasons and from year to year. In the extreme north and south of the two hemispheres they are very active during the winter, but much less so during the summer. It is to the movements of secondary cyclones that rapid changes of weather are due, the more prolonged changes in the conditions of pressure and temperature resulting from variations in the strength of the primary cyclones.

Before dealing with cyclones of a secondary character it is advisable to refer again to the main features of the great Antarctic and Arctic cyclones as illustrated in Figs. 59 and 60, which show the general circumpolar movements of the lower troposphere. Indeed, there is every reason to believe that the air movements in both large and small cyclones are similar, and that the circulation of the trade winds is of quite a different character.

Owing to the simplicity of the wind circulation in the Southern Hemisphere attention for the moment may be confined to this region. The great cyclone which is centred

over the South Pole persists with great regularity the year through. It occupies about one-quarter of the earth's surface, its northern boundary being the southern "horse latitudes." The direction of the air circulation in it is shown in Figs. 59 and 60. This circulation cannot possibly result from the surface temperatures of the area, nor can it be due to any extraneous dynamical effect. Apparently the only possible source of energy which could produce the whirl is a high temperature and low density in the stratosphere over the poles, overpowering the adverse influence of a comparatively high density in the troposphere. Such temperature conditions as would cause a circulation of this kind are shown in Fig. 68. Here the stratosphere temperature over the poles is shown to be high at high levels, and the isotherms must produce a dome-shaped mass of air above. The air of this "dome" moves away at high levels in all directions, with the result that the pressure falls over the heated area even at low levels. The distribution of temperature that produces the "trades" is not of this kind, for in equatorial regions it is the low-level heated air near the equator that lowers the pressure there and induces an inflow of air. At moderately high levels the gradient is reversed. Under such conditions of pressure the direction of the winds in the troposphere would be as shown in Fig. 61.

If the air were a frictionless fluid, and the earth's surface were frictionless, cyclones would persist, the winds everywhere having exactly the velocity dictated by the pressure gradient and earth's rotation, until the air movement destroyed the pressure and temperature gradients. However, the air is not frictionless, and the greatest resistance to flow is where it comes in contact with the ground. Over the oceans the friction is less. This friction reduces the velocity of the air, and as a result it moves in spirals towards the cyclonic centre, and rises near the centre of the cyclone. However, it cannot cross the tropopause in any volume, and on reaching the upper portion of the troposphere it moves outwards again, but still continues to circulate in the direction demanded by the law of Buys Ballot. But the conditions of pressure in the troposphere and stratosphere are both comparatively low, and on this account the air at the bottom of the stratosphere, immediately above the tropopause, as a result of viscous friction, moves in the same general direction as does the air of the top of the troposphere, *i.e.* outwards and in the Northern Hemisphere anticlockwise. However, with increasing height, this outward movement must slow down, and reverse before a height of

20 kilometres is reached. At higher levels, as already stated, the movement is anticyclonic. On Fig. 61 these wind conditions of the troposphere are shown by arrows both in plan and section.

We shall see that the study of secondary cyclones of the Northern Hemisphere reveals the fact that the tropopause is much depressed in them, especially when they are deep ones, and it would appear that the tropopause must be in general nearer the ground in the Antarctic than in the Arctic, and this in spite of the fact that there must be a slow passage of air upwards across the tropopause. This depression of the tropopause is attributed to some extent to the interaction of the winds above and below it, but primarily to heating above it. However, we know little concerning the cyclonic conditions of the Antarctic Continent, it being impossible to draw synchronous charts for the area owing to lack of data.

The low-pressure centre of the Antarctic Cyclone, it appears, coincides approximately with the centre of the Antarctic Continent and isotherms of the Southern Hemisphere, and this contributes to the general simplicity of the structure. In the case of secondary cyclones this simplicity does not obtain ; for these cyclones, in middle latitudes, are impressed upon areas over the whole of which there previously existed fairly regular pressure and temperature gradients, these gradients having become much distorted by the movements of the secondary cyclones.

During recent years our conceptions respecting the conditions obtaining in cyclones have undergone very considerable modification. The old idea, which made a cyclone consist of a lower spirally inflowing current of warm air directed towards the centre of an area of low barometric pressure, an internal rising current of warm air, and an upper stream of air flowing outwards from the same centre, requires considerable modification in view of modern discoveries. The rising air in the troposphere is not, comparatively speaking, warm. It is cool, considering its height, and has evidently been raised by the forces maintaining the cyclonic movement.

Fig. 52 is a diagram, after W. H. Dines, showing the distribution of temperature in a cyclone about 2,000 miles in diameter. It will be noticed that the temperatures below the tropopause are lower in the centre than at the margins of the depression. It is clear, therefore, that the temperature gradient, but not the pressure gradient, is such as would cause air movements on the ground opposite in direction to

that which the winds actually take, and that, therefore, it is the low pressure that causes the movement. On this account the old theory that a cyclone results from the ascent of warm air in the troposphere must be abandoned.

However, in the stratosphere the temperature not only rises as the height increases, but over the cyclone, as a result largely of the lowering of the tropopause, there is a mass of heated air. It is here suggested that this relatively heated air extends to the confines of the atmosphere, where the high temperature is sufficiently pronounced to produce an elevated air dome, which gives rise to a strong density gradient for the flow of air outwards. The lateral displacement of this air reduces the weight of an air column which then becomes the warm low-pressure centre of the cyclone, and the resultant low air pressure is felt right down to the earth's surface. This feature is common to both primary and secondary cyclones.

The conditions in the troposphere give point to a remark by Sir Napier Shaw, in a preface to Gold's paper on the "Barometric Gradient and Wind Force," to the effect that "the whole question of the cause and meaning of the discrepancies between the gradient wind and the actual wind is, of course, bound up with the question of pressure differences. To put the point in a crude form, I do not know whether, in practice, the winds have to adjust themselves to the pressure conditions, or the pressure distribution is the result of the motion of the air." The standpoint taken in this present work is that in perhaps all cyclones the pressure conditions are impressed upon the area by high temperatures mainly in the stratosphere, and that the winds are compelled to flow as the resulting local isobars and density gradients dictate, even to the extent of creating somewhat opposing temperature gradients by vertical air movements and checking flow near the cyclonic centre. According to this conception the low pressure of the cyclone is caused and maintained by the buoyancy of local masses of warm air largely in the stratosphere. The actual movements of the winds in a cyclone obey the resultant effect of local density and pressure distributions, and are modified by the friction the moving air meets with at the earth's surface, the constraint of the conditions imposed by imperfect convective equilibrium, and the previous conditions of air flow in the area upon which the low pressure is impressed.

In the case of the great high-latitude cyclones, such as that of the Antarctic, the air above them must be continually reheated by fresh supplies of energy, and the direction of

the winds and the distribution of temperature must often approach that of a "steady state." With secondary cyclones the case is different. They seem to become heated by temporary local supplies of energy, come into existence quickly, and fill up rapidly. Their life period is often so short that they make only a small fraction of a revolution during their lives. Whilst they exist, such short-duration cyclones, however, show a good deal of detail worthy of consideration.

Both theory and fact point to the conclusion that the radiation which causes the heating which results in cyclones strikes the atmosphere around the magnetic poles, which are some distance from the poles of the earth's axis.

The daily charts of the weather conditions issued by the Meteorological Office in the case of high latitudes are compiled from a comparatively limited number of observations, and as a rule do not show many of the minor but nevertheless important features of the cyclones. However, a few cyclones have been studied in more detail, and it is to these that we must look for information concerning their many interesting minor features. We must remember that many cyclones travel along the earth's surface very rapidly, and the question naturally arises whether the air they disturb is travelling along with them, or whether they are involving in their internal movements air which they pick up on their fronts, leaving behind them air which has ceased to be concerned in their whirling movements. A smoke ring projected from a tobacco pipe travels through the air and takes smoky air with it. A study of cyclones seems to tell us clearly that in some cases a portion of the air travels with the cyclone for considerable distances, and that sometimes it does not.

When the cyclone is involving fresh air in its front and is rejecting air in its rear, it would appear that the mass of very warm air in the upper stratosphere is travelling over air in the lower troposphere which is moving much slower, or in a different direction. In this way low pressures are impressed on successive air masses near the earth's surface as the upper warm air drifts along.

Shaw and Lempfert have investigated the actual paths followed by the lower air in different cyclones. One such cyclone which passed over England on March 24, 1902, is indicated in Fig. 70. It was clearly involving new air masses as it advanced. Figs. 71 and 72 show some of the trajectories of this cyclone. The dotted lines give the direction of its motion. By taking points in the neighbourhood

of the cyclone, and drawing lines on pieces of tracing paper in the direction the arrows showed the air was moving, short lengths of the trajectories were obtained. The tracing paper was then placed upon the next chart and the lines continued in the direction of the wind. This process was repeated until the cyclone had moved for about 24 hours. The figures on these trajectories, and on the dotted lines showing the course of the cyclone, show the hours of the day.

Three points among those selected for treatment, on being followed up produced the flat curves *A*, *B* and *C*, Fig. 71, and it will be noted that they indicate air movements from the south-west. Each of these curves meets the line along which the cyclone was travelling so as to plunge into the region of indefinite wind near its centre. It was found impossible to follow the air movement any farther, and it was concluded that this air had left the surface and been deflected upwards.

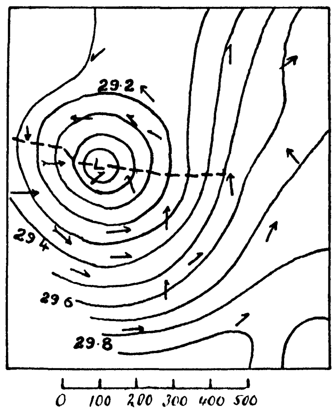


Fig. 70.—Cyclone of March 24, 1902.

Other trajectories *D*, *E*, *F*, *L* and *N*, Fig. 72, start from points at such times that the air flow they indicate comes from the south or south-west, and from places some distances in front of the depression. They thus pass across the front of its track, loop round, and then move to the south-east.

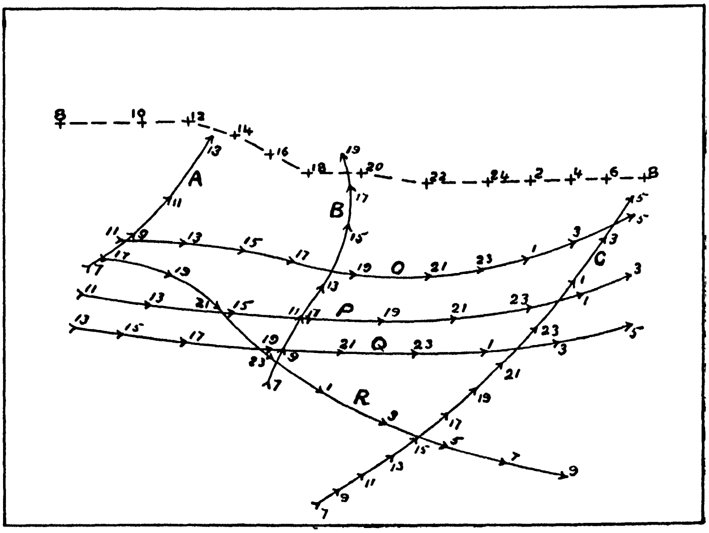
The air tracks *O*, *P* and *Q*, Fig. 71, start from places to the south-east of, and a little behind, the cyclonic centre, and then flow from west to east on the south side of the cyclonic centre. The cyclonic centre has about the same velocity as the westerly wind.

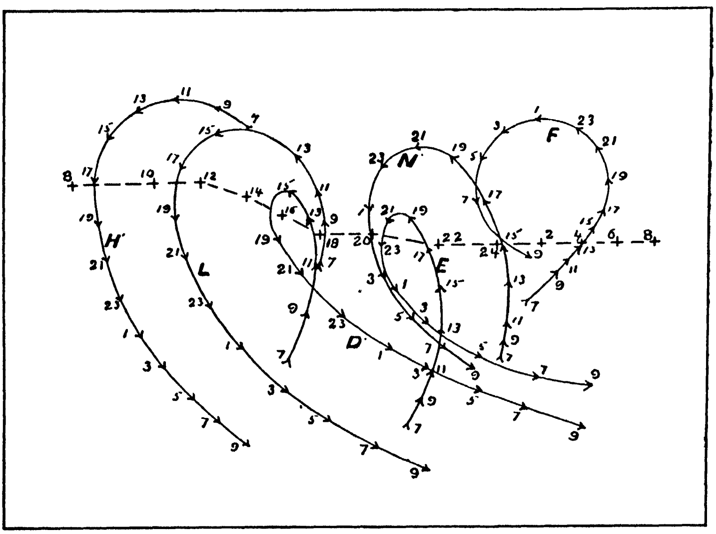
The trajectories representing the flow of the winds of a *travelling cyclone* do not support the idea of a gradual approach of the air towards the centre in all parts of the system along spiral curves ; for we find that air is fed into the system by the southerly or south-westerly winds in front of the depression.

The air movements represented by the south-westerly winds such as *A*, *B* and *C*, which end in the calm or indefinite wind area near the centre, must be deflected upwards, a motion which has been explained to be intimately connected with the production of cloud and rain.

If we trace the weather along any of the looped

trajectories we find that rain sets in sooner or later in the course of the motion from south, south-east or south-west, and continues until the northernmost point of the loop is





Figs. 71, 72.—Trajectories of Cyclone of March 24, 1902.

reached, or even a little longer. When the motion is directed towards the south again steady rain ceases.

When the cyclone is *stationary*, the air does generally converge on the centre from all directions, and the distribution of the rainy air is different from the case just illustrated. Speaking of tropical American cyclones, Clines notices this

difference. Very little precipitation was found by him to occur in the rear half of travelling cyclones. The greatest precipitation intensity in the larger cyclones was found to be 60 or 80 miles in front of the centres and mostly to the right of the line along which they were advancing. In all the travelling cyclones the precipitation almost ceased with the lowest barometer reading. In three cyclones which ceased to advance, on moving inland from the sea, the greatest hourly precipitation, which had first occurred in

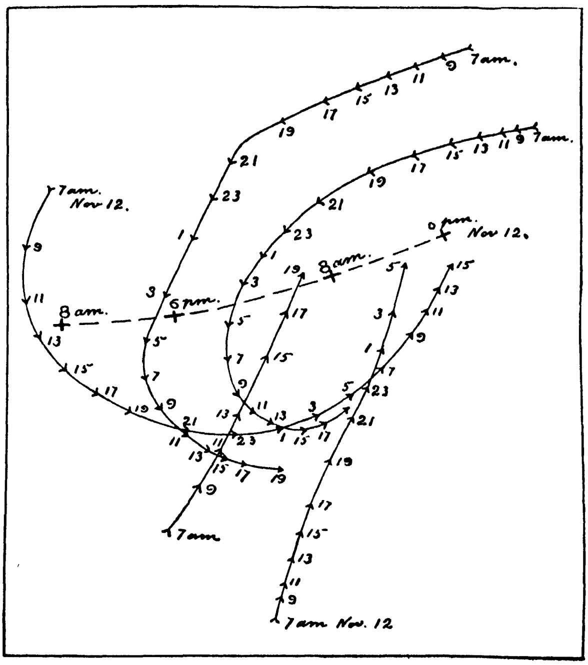


Fig. 73.—Trajectories of Cyclone of November 12, 1901.

the right front quadrant whilst the cyclone was advancing, shifted to the rear of the cyclone as it stopped travelling.

Another depression, the trajectories of which are shown in Fig. 73, which differed in some noteworthy respects from the one just considered, moved slowly over England on November 12, 1901. The wind over France, Germany and the south-east of England blew from the south-west. An easterly wind from the Baltic cut off abruptly the south-westerly wind, and "backing" as it travelled round the western side of the depression finally became a northerly wind. The average rate of motion from west to east was only about 17 miles per hour, whereas in one locality the velocity of the wind was 59 miles per hour. The rainfall

was exceptionally heavy, four inches being recorded at several stations in Ireland. The area of precipitation was a broad band stretching from west to east along the line separating the south-westerly wind from the easterly Baltic wind. As might be expected, the air from these two sources was at decidedly different temperatures, and it is suggested that the process going on in the depression was that the warm moist air from the south was rising up over the cold air from the north-east. The fact that rain was falling in Scotland when the depression was well over the North Sea shows that the south-westerly wind, after rising over the easterly wind, curved round ("backed") and passed to the north and west of the cyclonic centre. A peculiar feature of the depression was an area of westerly wind, south-west of the cyclonic centre, which travelled with the cyclone. Fig. 74 shows the isobars of this cyclone, the wind provinces being separated by thick hatched lines.

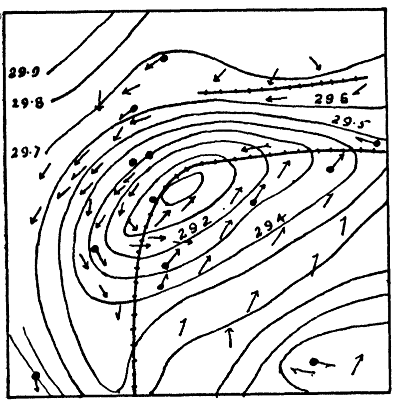


Fig. 74.—Isobars of Cyclone of November 12, 1901.

The trajectories of the surface winds of the cyclone of November 12, 1901 (Fig. 73), were quite different from those of the cyclone of March 24, 1902 (Figs. 71 and 72). The curves in Fig. 73 show a plentiful intake of air from the south, but in addition we have distinct evidence of a separate supply from the east. This supply from the east "backs" and passes to the west of the depression.

When a cyclone is impressed upon a district, or advances approximately at right-angles to the isotherms, which is somewhat rare, as the rotating cyclone moves, the original ground isotherms undergo great changes. Fig. 75 shows these changes in a severe American storm as it appeared at 8 a.m. on November 25, 1895, when its centre was over the Mississippi between the junctions with it of the Arkansas and Red Rivers. The low-pressure area extended well up to the Lake District, the line of advance being shown by the arrows. The velocities of the winds were, at Detroit 76 m.p.h., at Cleveland 72 m.p.h., and at Erie 60 m.p.h. During the northward movement of the storm there was a general rise in temperature of the region east of the Mississippi. The cold isotherms on the west side

travelled a long way south, whilst the warm ones on the east moved north. Freezing temperatures were produced as far south as the central portions of the Gulf States, and frosts along the East Gulf Coasts and in Northern Florida.

The reason why the displacement of the isotherms was not greater than the figure shows it to have been, is that the cyclone was large in diameter, and that although it lasted several days, its life was really so short that it had no time to complete more than one quarter of a revolution at a short distance from the centre. Indeed it is remarkable how little, broadly speaking, such cyclones disturb the air conditions upon which they are impressed from above. However, near their centres they often complete several revolutions and destroy all trace of previous conditions.

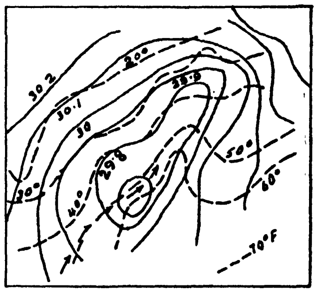


Fig. 75.—American Cyclone of November 25, 1895.

It has been suggested that such cyclones derive their energy owing to the cold north winds clinging to the ground until the warm south winds eventually flow over them. It is difficult, however, to imagine this taking place in cyclones existing as far north as Spitzbergen. Indeed the south-west winds nearly always force their way north, in the Northern Hemisphere, against the cold air of high latitudes, owing to favourable pressure gradients—the north winds should flow down to the "horse latitudes" if the movement were produced by troposphere temperature gradients. It is clear that the winds concerned are flowing in accordance with pressure gradients caused by a temperature distribution of what appears to be an abnormal character, and it is certain that the warm winds when they get well into high latitudes have been caused to move there in accordance with the dictates of pressure conditions, but often then mount over the thin cold layer of polar air.

When low-pressure conditions do not exist in high latitudes, as is shown in Fig. 122, Curve *A*, the cold winds spread south along the earth's surface in accordance with the pressure gradient.

The illustrations given of the whirling movements of cyclones when they involve considerable areas over which there is a fairly steep temperature gradient suffer from want of detail. Much of the misunderstanding concerning cyclones arises from the feeling of some meteorologists that

details concerning the anatomy of these disturbances are not of great consequence. The fact is that cyclones, and the general circulation of the atmosphere, will never be properly understood until we have detailed studies of the anatomy of cyclones great and small, and unfortunately the number of observing stations is generally too few for such charts to be made.

When we study cyclones it is generally seen that there are two or more areas each dominated by different currents of air. These have been called "wind provinces" for convenience.

Another cyclone is shown in Fig. 76, which reproduces

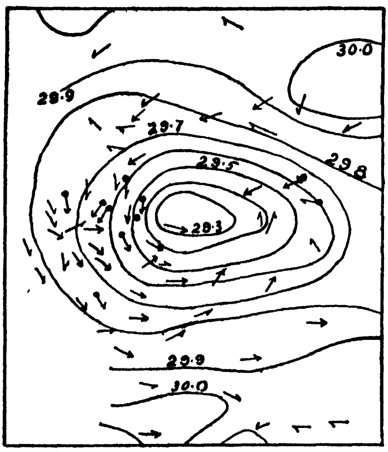


Fig. 76.—Cyclone of October 7, 1903.

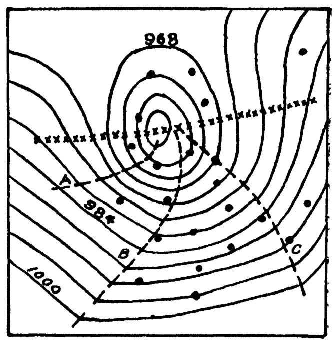


Fig. 77.—Cyclone of November 23, 1928.

many of the features of those already described. It was of the slow-travelling type, moving from west to east at about 11·5 miles per hour. It originated over the west of the British Isles and grew deeper and deeper as it moved in an easterly direction. At the time of its formation, October 7, 1903, there were south-westerly winds over the area and easy pressure gradients. At 8 a.m. on October 8 there was a well-marked but shallow depression over the south-west of England. An inflow set in from the Baltic area, the southerly wind commenced to rise over it, and rain fell in the northern counties of England. These features had become well marked at 8 a.m. on October 9, and the depression amounted to 0·6 inch of mercury, rain falling where the black dots are shown.

The cyclone shown in Fig. 77 passed over Scotland on November 23, 1928. The black dots show where rain was

falling. The cyclone was of considerable depth and intensity, the isobars ranging from 1,000 millibars at its margin to 956 at its centre. There were several wind provinces, separated by the dotted lines *A*, *B* and *C*, and it is interesting to note that the isobars changed their directions abruptly as they passed from one province to another. Rain was falling over practically the whole area, and this indicated that the air currents were being bunched together and caused to rise.

V. Bjerknes and others have closely studied the anatomy of cyclones, and lay great stress upon the discontinuities or "fronts" which radiate from the central area of low pressure. It is not necessary here to deal with the question in any detail. It is sufficient for our purpose to note that the whirling motion of a cyclone which develops rapidly, as did that which passed over the British Isles on November 23, 1928, and shown in Fig. 77, draws a good deal of air towards the centre of low pressure, and also greatly distorts the isotherms. As a result of these movements air currents undercut or override each other.

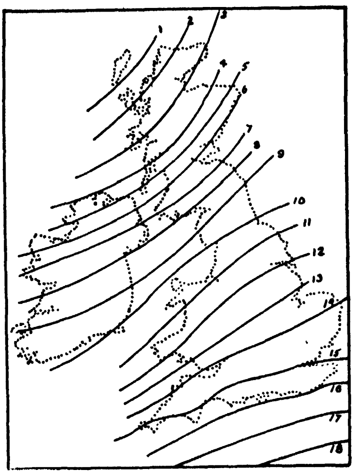


Fig. 78.—"Line Squall" of February 8, 1906.

The two principal discontinuities seem to be those Bjerknes calls the "steering-line," with its fore-runner, and the "squall-line" with its fore-runner. Such lines of discontinuity are often of great length and are known as "line squalls." One such line passed over the British Isles on February 8, 1906, and is shown in Fig. 78. The full lines show the movement from hour to hour. "Line squalls" are very interesting phenomena met with along the line separating two air currents, being very marked when the winds on their two sides are of sensibly different temperatures and inclined to one another at a considerable angle. In the case we are considering, a westerly or north-westerly wind was displacing and undercutting a south-westerly current, and where this occurred the isobars suffered a sudden change of direction. As the disturbance passed over London there was a violent thunderstorm, accompanied by a violent squall and a sharp fall of hail and snow, and the wind shifted from the south-west to the north-

west. There was also a fall of temperature from 44° to 37° F.

In a depression of another type the isobars are V-shaped. The trough is the line through the centre, where the isobars make a sudden bend. In the neighbourhood of the British Isles the motion is generally towards the east. In front of the advancing trough the winds are blowing from the south, whilst to the north-west the wind is north and north-west. In such V-shaped depressions the weather sequence is similar to that of a circular cyclone. As they advance, the first result is the formation of cloud, followed by rain. In the trough the clouds are broken and showery weather follows. The clearing shower occurs as the wind suddenly changes its direction.

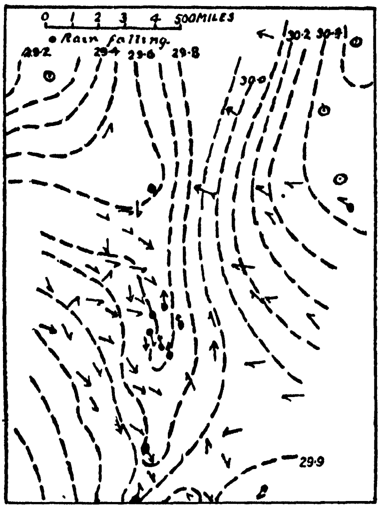


Fig. 79.—V-Shaped Depression of January 7, 1900, at 8 a.m.

Such a V-shaped depression (Fig. 79) formed over England during the interval from January 6 to 8 in 1900. There was a low pressure over Ireland, and a tongue of it was thrust in between a high-pressure area over Scandinavia and another in the Bay of Biscay. Fig. 79 shows the conditions at 8 a.m. on January 7. The depression subsequently extended in a south-westerly direction, low pressure still holding to the north-west. It shows a sharp southerly wind, with westerly winds to its west, and easterly winds to the east. The southerly wind is moving at a low angle across the isobars, from high to low pressures. The rain was considered by Shaw and Lempfert to have been due to the mounting of the damp southerly current over the northerly and westerly wind on its westerly margin.

Occasionally cyclones, accompanied by rain, do occur, which show, even as far as their lower levels are concerned, a striking resemblance to the old theoretical cyclone. Fig. 80 represents such an one. Its centre lay over the sea between Wales and Ireland. The wind directions show that the air was circulating around the centre of the depression, and was rising over the whole of it, with the exception, perhaps, of a small area to the south-west. The disturbance was travelling from west to east at a velocity of about 35 miles per hour,

and the wind velocities were high. The irregular nature of the wind directions shown by the arrows is most probably due to the flow of air from areas of heavy rainfall, resulting from the mechanical effect of the falling rain. To the east of the storm centre, in the direction of Holland, a south-westerly wind and westerly wind were in conflict, and rain was the result there as well as near the centre.

A very obvious case of a rising wind producing rain, without any marked barometric changes, is described by Shaw and Lempfert. The wind directions are shown in Fig. 81. Here we have a wind from the south-west blowing against one coming from a little west of south. The line separating the two wind provinces was moving eastwards

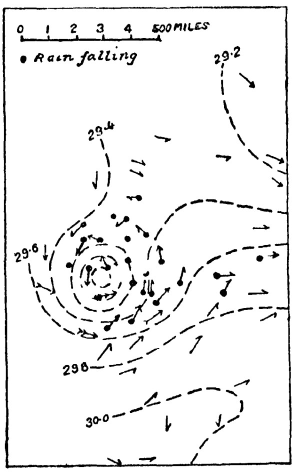


Fig. 80.—Cyclone over Irish Sea, September 10, 1903.

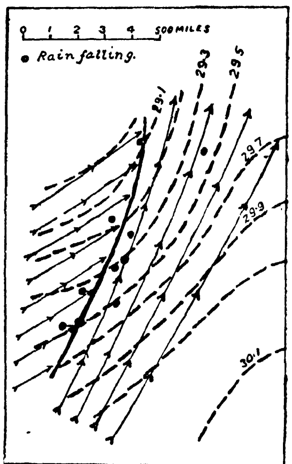


Fig. 81.—Showing Wind Discontinuity.

at about 29 miles per hour, whereas the wind following it up was moving only at 20 miles per hour. Rain was falling near to and on both sides of the dividing line between the winds. The upper portion of the westerly wind appears to have been travelling more rapidly than the portion near the ground, and was descending and forcing itself beneath the more southerly wind. The latter being forced to rise precipitated some of its moisture through the lower south-westerly wind as well as along its westerly margin.

It has been shown that although the winds and pressures in cyclones are in close agreement, and obey Buys Ballot's law, the sea-level isotherms generally indicate that, at low levels, temperature conditions are only of secondary importance outside the tropics. The view that, if we are to understand low-level phenomena, we must consider

phenomena that take place at very great heights, has been strengthened by the facts that have come to light concerning the rôle played by ozone in the upper atmosphere. This substance consists of three atoms of oxygen combined to form a molecule. As Table I (p. 27) shows, it is present in the atmosphere only in very small quantities. However, the effect of even a small quantity in the upper atmosphere is very marked, for the gas is practically opaque to certain rays of ultra-violet light, and we can deduce the amount of ozone present by measuring the actual strength of the ultra-violet light that reaches us, as compared with the strength of other light rays. If all the ozone ordinarily in the upper atmosphere were collected into a layer at the sea-level it would be 3 millimetres thick. Even this very small amount of ozone has important effects, inasmuch as it prevents the excessively strong ultra-violet radiation from the sun from reaching the earth in any quantity ; such radiations from the sun, if they reached us without diminution would, among other things, cause intense sun-burns.

By certain methods of observation, which it is not necessary to describe here, it has been ascertained that the ozone layer lies at a height of about 20 kilometres. To the meteorologist the point of interest is that the ozone is most plentiful above low-pressure areas, and least plentiful over high-pressure areas. That ozone is formed by some action connected with the auroræ is doubtful. Prof. Chapman considers that the observed facts can be accounted for without assuming any other ozone-producing agency than the sun's ultra-violet light.

Figs. 82 and 83 show the result of plotting pressures and ozone figures in the case of a typical cyclone and anticyclone. At the level of the ozone layer there would appear to be an indraught of air towards the cyclonic centre, and it is possible that the high density of the ozone over the cyclonic centre is due to indraught of ozone from the surrounding area.

The number of observations made showing the density of the ozone layer is as yet comparatively small, and as a consequence it is not possible to say with certainty how meteorological changes vary with alterations in the transparency of the ozone layer. However, observation favours the inference that all over the earth the lower the pressure the denser the ozone layer.

The mean amount of ozone in the atmosphere is, as already stated, about equal to that which would be com-

prised in a 3 mm. layer of the pure gas at the earth's surface. In Figs. 82 and 83 the values are expressed in differences from the mean for the time of the year, so that the figures show in units of 0·001 cm. the distribution of ozone in cyclones and anticyclones.

The hurricanes and tornadoes of the equatorial seas are also cyclonic in character, but have peculiarities of their own which make it somewhat doubtful as to the extent to which they are affected by occurrences in the stratosphere, even when they travel into middle latitudes. There are some cases, however, such as the hurricane of August 17th–22nd, 1915, which passed through the Yucatan Channel and reached Galveston on August 17 and then moved in a

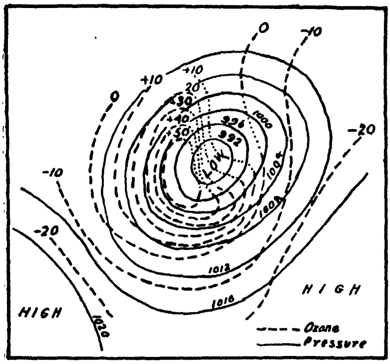


Fig. 82.—Distribution of Ozone in Cyclone.

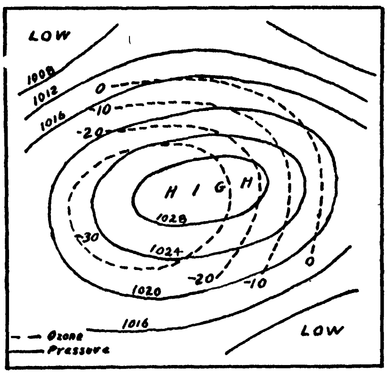


Fig. 83.—Distribution of Ozone in Anticyclone.

north-westerly direction over the Great Lakes into the St. Lawrence Valley, which makes them appear as though they had been affected by heating from above. It would be interesting to know if, at any part of their courses, such cyclones were at their centres accompanied by ozone in excess of the usual mean. These West Indian hurricanes seem to travel with the prevalent lower winds, and, as they reach middle latitudes, develop some of the peculiarities of high-latitude cyclones. They may be caused, as are the trade winds and anti-trades, by the intense heating of the moisture-charged atmosphere in the neighbourhood of the earth's surface, but, as has been pointed out, there are difficulties in the way of this view.

It would be difficult for large areas of heated air at low elevations to give rise to cyclones of large area. The few thousand feet of the atmosphere involved is so thin, as compared with the area involved, that the tendency would rather be for multitudes of descending streams of cold air to

develop, with intermediate ascending streams of warm air. Over desert areas in the heat of the day we may see many whirlwinds of comparatively small diameter dancing and twirling about each other in all directions. They carry up the sand grains and dust, which render them visible to heights of many hundreds of feet.

However, a large heated area of high land may undoubtedly form a cyclone, for the air is then directed upwards towards the centre by the mountain slopes, as is the case with the low-pressure area over Asia which causes the Indian wet Monsoon. However, if radiations from the sun, such as those which produce cyclones in the Arctic

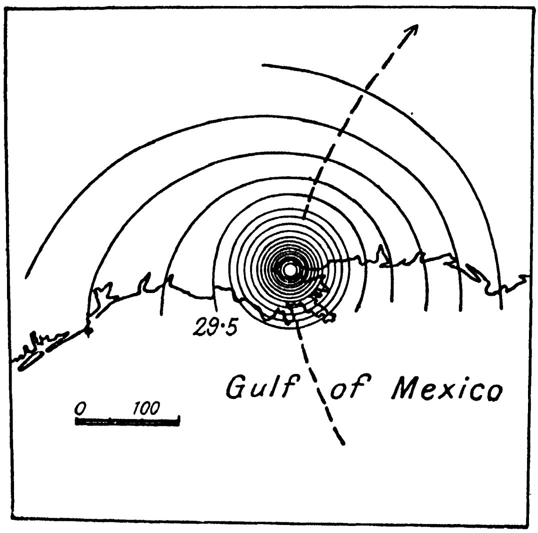


Fig. 84.—American Cyclone of September 29, 1915.

night, struck the upper atmosphere occasionally in the tropics, in spite of the earth's magnetic field, cyclones would immediately tend to form.

Fig. 84 shows the cyclone of September 29, 1915, which has been described by Clines, when it was over New Orleans. The isobars are drawn so as to represent differences of 0·1 inch of mercury. In three of the largest West Indian cyclones, including the one shown in the figure, the isobars are nearly circular from the centre outward to 29·4 inches inclusive ; outside this isobar they show a crowding on one side and a spreading on the other side. In front of their paths the rainfall is heavy ; but there is very little rain in the rear half, except when they cease to travel. The winds show a spiral movement inwards, but not a uniform movement all round.

Tropical cyclones are confined chiefly to the following areas:—

(1) Pacific Ocean to the east of Australia and Samoa.
(2) Indian Ocean to the east of Madagascar and Mauritius.
(3) The China Sea and the Coasts of Japan.
(4) The seas on both sides of India.
(5) The West Indies and Gulf of Mexico.

No region of tropical cyclones is found on the eastern side of an ocean; they are all on the western sides, and all originate over the sea, seldom travelling far over the land.

The smaller whirling storms occurring in the valleys of the Mississippi and Missouri, called *tornadoes*, are on an average about 1,000 feet in diameter, and are exceedingly destructive owing to the high velocity of the whirling winds. They last at the most a few hours, and occur mainly in the spring and summer during the afternoon. They occur on the southern side of a depression, and move eastwards and north-eastwards. A marked feature is the funnel-shaped cloud stretching from the storm cloud to the earth's surface, and they are always attended by violent thunder and lightning. They appear to result from the same cause as hurricanes, but are very much smaller in diameter. Sometimes several of them may be seen moving along not very far from each other.

Whirlwinds, which may be seen moving in irregular curves over sandy deserts, have characters similar to those of tornadoes, but owing to the absence of water vapour there is no cloud above them, and they are not so intense. They are rendered visible by the sand and dust they raise. Both tornadoes and whirlwinds, when they pass over water, draw it up and form waterspouts.

Monsoons are seasonal winds due to variable heating of air, land and sea as the sun's altitude changes from day to day. The name is from the Arabic *mausim*, a "season," and the early European traders and Arabs regulated their voyages by them. Sometimes seasonal changes affect only the strength of the winds, but occasionally they actually cause a reversal of the air currents and produce very important climatic effects.

Fig. 27 shows the area affected by the Indian Monsoon, an area of low pressure forming over Asia in the summer. Dr. C. G. Simpson has made a careful study of the phenomena the Monsoon illustrates. It is not a simple result of a single physical condition, but the result of a

combination of circumstances involving the consideration of temperature, pressure, humidity, the effects of the distribution of land and water, the rotation of the earth and the distribution of mountain ranges. All these influences are very regular in their action, yet the Monsoon varies greatly in strength from year to year. However, the cause of such variations may be in the stratosphere.

An inspection of Fig. 27 shows that the lowest pressure over India is in the extreme north-west, from which, during July, it rises steadily to latitude 30° S. This results in the reversal of the northern trade winds of the Indian Ocean, with the result that the humid heated air both north and south of the equator is driven against the west coast of India and also over Eastern India against the Himalayas. During the winter the high plateaux become intensely cold and anticyclonic conditions supervene. The flow is then outwards, and the trade winds re-assert themselves over the Indian Ocean north of the equator. This is the season of the Dry Monsoon.

It will be seen that the great Asiatic mountain mass has a profound effect upon the weather conditions of the Northern Hemisphere, especially in the Northern Indian Ocean; for the mountain ranges rise over an immense area above the lower winds, and thus interfere with the proper development of cyclonic conditions in the Northern Hemisphere to match those of the Southern Hemisphere.

We have seen that rain results from the rising of moist air, as in the "doldrums," the moisture first being thrown down as cloud, owing to expansion. Such condensation takes place on dust particles and ions until the drops are sufficiently heavy to fall rapidly. Where the air descends again in the "horse latitudes" little or no rain falls, compression warming the air and making it relatively dry. This dry air moves north and south from the "horse latitudes," and as it moves over the oceans picks up moisture; but that portion which moves under the influence of the pressure gradient towards the poles becomes chilled, with the result that much rain is thrown down between latitudes 40° and 50°.

Another type of rainfall results from the winds of the general circulation passing over or impinging upon more or less mountainous continental areas and islands. When the winds are able to pass over or rise up the slopes of such areas, heavy rain results. However, much depends upon the season of the year, for in the summer cyclonic conditions are apt to develop over large land areas, whereas in the

winter anticyclonic conditions are apt to prevail. These effects are much complicated by the march of seasons as the sun moves north and south of the equator.

If it were not for the fact that air is caused to rise and fall by the passage of secondary cyclones, especially in middle and high latitudes, rains would be much more local than they are, and the air, especially over the oceans, would be more saturated with water vapour. Indeed, we are indebted to cyclones for much of the rain that falls over oceans and low lands, and also for the comparative absence of sea mists and fogs.

The charts of the weather we have to be satisfied with do not represent the actual conditions in detail prevailing over the regions they cover. They are drawn in accordance with meagre information, obtained at stations considerable distances apart, and as a result all the smaller but nevertheless important details are smoothed out when the isobars, isotherms, etc. are put in. In a few cases only have attempts been made to show the anatomy of cyclones in detail. Every shower and every bank of clouds as it passes over modifies the winds and pressures. Indeed, a correct chart of a large area would be a complex of somewhat regular curves, with lines of discontinuity separating wind provinces. Especially would such be the case in unsettled weather.

It has not been possible in such a small space as could be spared for the subject here to give more than a mere outline of the Variable and Periodic Winds of the earth. However, for present purposes more is not necessary.

CHAPTER XI.

ATMOSPHERIC PRESSURES IN HIGH LATITUDES.

THE general phenomena presented by the atmosphere have now been considered in some detail, and we are in a position to consider the changes which are taking place from day to day over large areas. Hitherto most of our knowledge of what the conditions are over large areas have been obtained by the classification of more or less isolated observations obtained from time to time. From them it has been possible to construct mean pressure charts such as those figured in the Challenger Expedition Reports.

Mean results obtained in this way are of course very valuable indeed, but it is impossible to understand properly meteorological phenomena without the aid of synchronous charts covering large areas. However, owing to the publication during recent years of more complete daily charts of the Northern Hemisphere by the British Meteorological Office, we are now in a better position to judge how weather conditions change from day to day in middle and high latitudes.

We shall here make use of the British Meteorological Daily Weather Maps, and to some extent the Japanese Meteorological publications. In the case of the Antarctic regions we know so little of the atmospheric conditions of the area throughout the year that it is impossible to discuss the pressure and temperature conditions of the region with advantage. On this account attention will be mainly directed to the Arctic regions and middle latitudes of the Northern Hemisphere.

The British Daily Charts cover an area centred near Godhaven on the west coast of Greenland, and consequently the area covered extends to lower latitudes over North America and the Atlantic Ocean than it does over Asia and the Pacific Ocean. However the maps only occasionally give information concerning that portion of Asia lying between 90° and 180° East longitude; but the Japanese daily charts often assist in this respect.

It is not intended to deal in any detail with weather conditions over the area. It is the pressure of the atmosphere

and its changes which will receive most attention. Until recently, little had been put on record concerning the atmospheric pressure changes which occur from day to day over large areas of the earth's surface, but we are now in a much better position to deal with the subject, for we have a fairly complete series of pressure charts for the years 1929–1932 inclusive. The study of a longer period would have been preferable, but the facts which the charts for the four years demonstrate throw much light upon the interdependence of the phenomena dealt with in previous chapters.

For our purpose three areas will be considered in some detail:—

(1) The whole area covered by the daily weather charts.
(2) An area which will be called the Arctic Area.
(3) An area which will be called the Atlantic Area.

The Arctic Area includes the whole region north of latitude 60°, with the exception of that portion extending from 90° to 180° East longitude. This area is selected for the purpose of ascertaining how the mean pressures vary from day to day in the extreme north as compared with those of the Atlantic Area, which extends further south and covers a large portion of Western Europe and Eastern North America, as well as the North Atlantic Ocean.

Attention has already been directed to the absence of any marked variations in the strength of the sun's radiations, and also to the fact that the light and heat rays have been considered as being entirely responsible for the temperature conditions of the earth's surface and of its atmosphere. Attention has also been called to the regularity with which the sun's heat is distributed over the continents and oceans from year to year and the regularity of the changes in the relative positions of the sun and earth which result in our seasons. Yet in spite of all this regularity we experience most marked and rapid changes in weather conditions, both from day to day and year to year. We also have to take account of the great climatic changes which have marked past ages, portions of the continents having been buried to a large extent at one time in great ice sheets and glaciers, whilst at other times semi-tropical conditions have existed on the shores of the Arctic Ocean.

It is important that the fact should be recognised that even now weather conditions are anything but stable. Indeed it has been calculated that if high-pressure conditions,

such as often exist over the poles, continued to exist for lengthy periods, the northern portions of our continents would soon be buried in ice again, and that if low-pressure conditions, such as frequently occur now, persisted, the polar areas would cease to be frigid. Indeed our present climates are largely the result of compromises between climatic extremes of short period.

To show how greatly the pressure conditions vary from time to time, a considerable number of synchronous charts are shown in this chapter. They show what a great variety of pressure conditions the earth, in high latitudes especially, experiences. Indeed an inspection of these charts alone

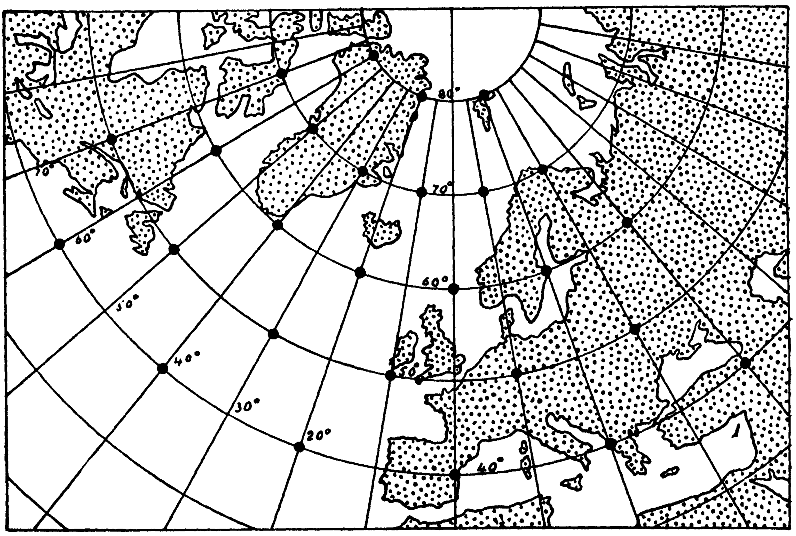


Fig. 85.—Pressure Chart of Atlantic Area.

raises doubts in the mind as to whether the sun's light and heat rays could really give rise to such irregularities, and compels us to consider whether they may not be due to some solar radiations of an irregular nature which have not been recognised by meteorologists.

Another valuable lesson may be learned by comparing the charts showing mean monthly conditions with those illustrating daily conditions ; for from the mean monthly isobaric charts it would scarcely be anticipated that the daily pressure conditions are so extremely varied in character and that the ranges of pressure are so great. For example, compare Fig. 113, which shows the mean isobars for April, 1930, with the synchronous chart, Fig. 115, for April 1, 1930.

For the Atlantic Area the daily mean pressures have been calculated for each day of the four years 1929–32, and from them the daily pressure ranges have been determined. For the Arctic Area the mean pressures have been calculated for 1929 and 1930.

The calculated mean daily pressures over the Atlantic Area are the means of 27 selected points, as plotted on Fig.

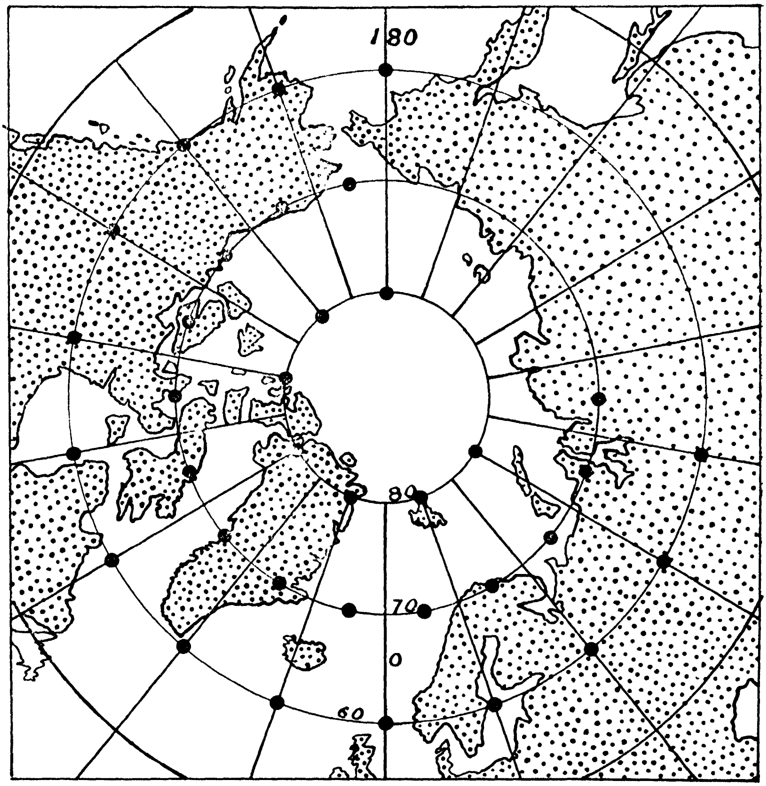
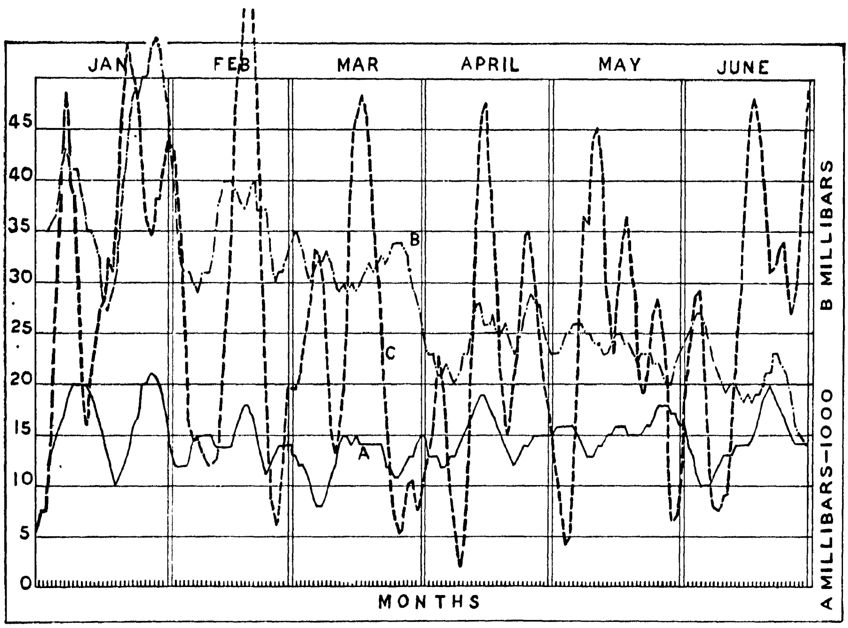
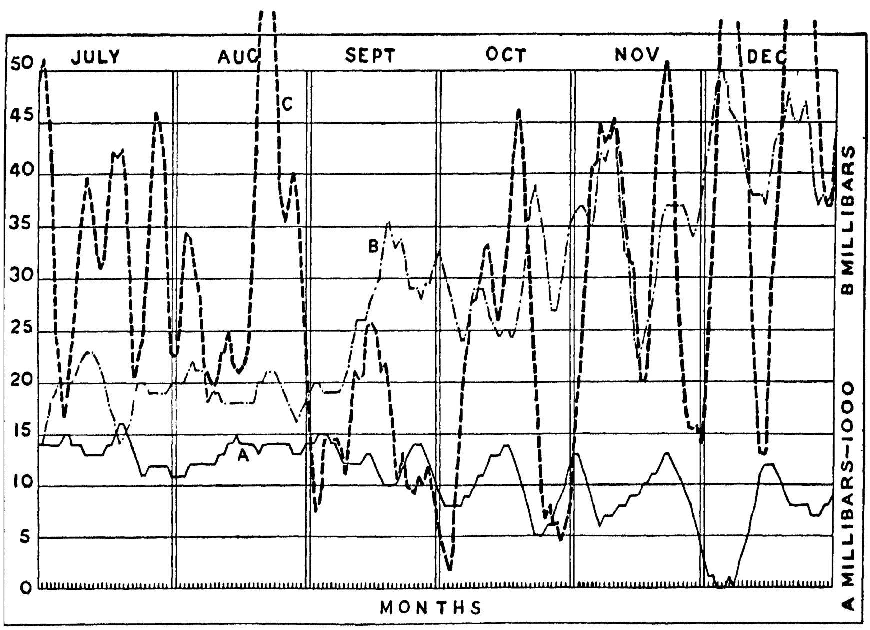


Fig. 86.—Pressure Chart of Arctic Area.

85, and for the Arctic Area of 35 selected points, as shown in Fig. 86.

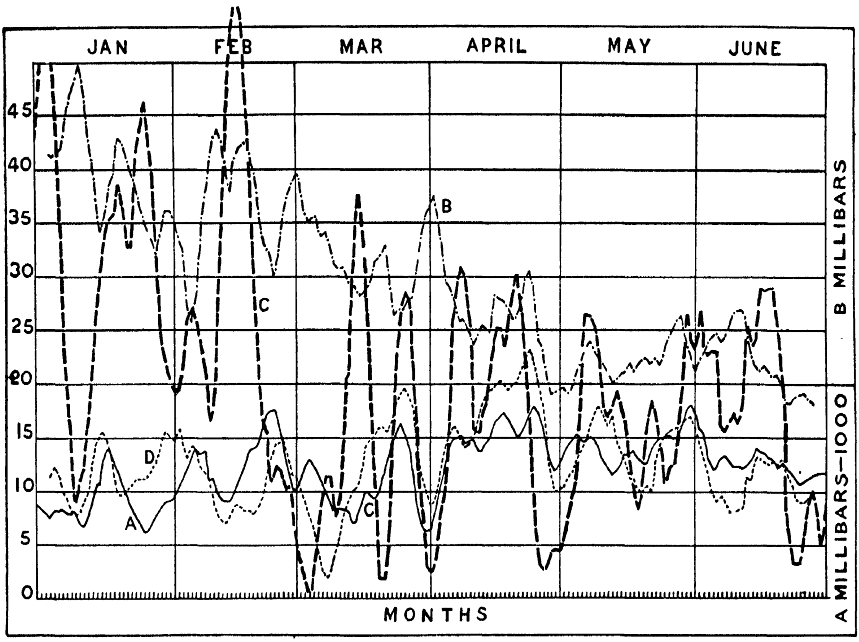
The mean daily pressures and pressure ranges, smoothed for five days so as to eliminate to some extent very short period fluctuations and errors of observation, are shown in Tables XIX to XXVI of Appendix, for the years 1929–1932 inclusive. They have been plotted on diagrams Figs. 87 to 94, along with sunspot figures, to enable the remarkable pressure changes which are constantly taking place to be easily seen.

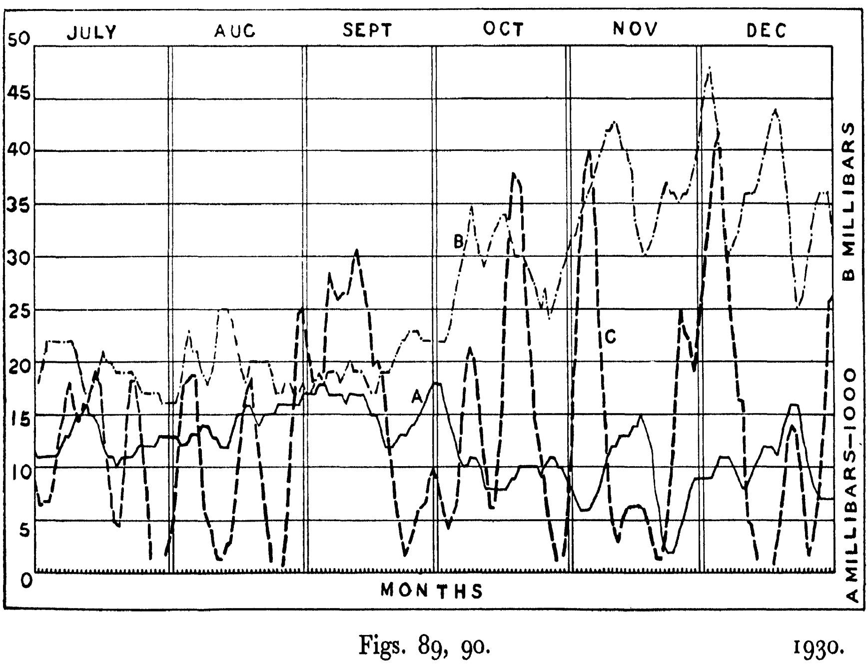




Figs. 87, 88. 1929.

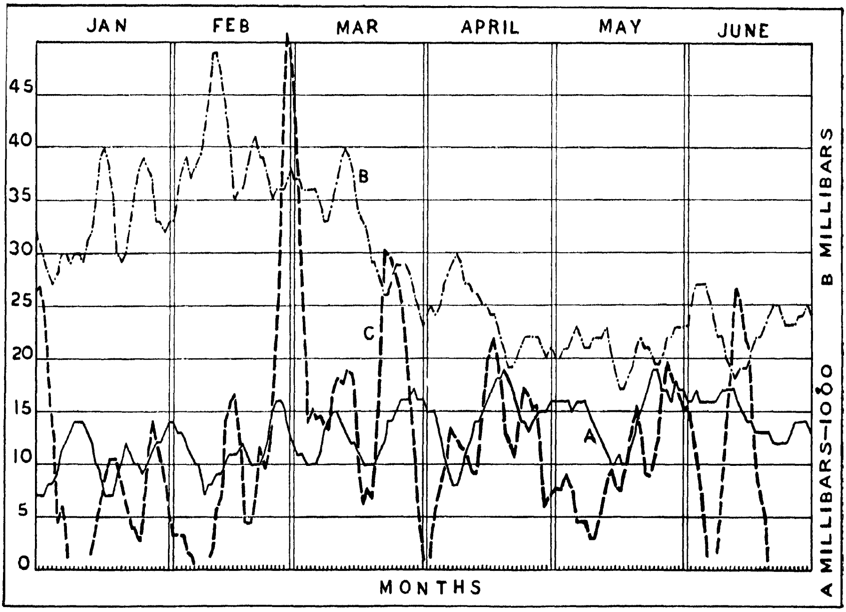
(A) Atlantic Area Mean Pressures ; (B) Atlantic Area Pressure Ranges ; (C) Wolf Sunspot Numbers.

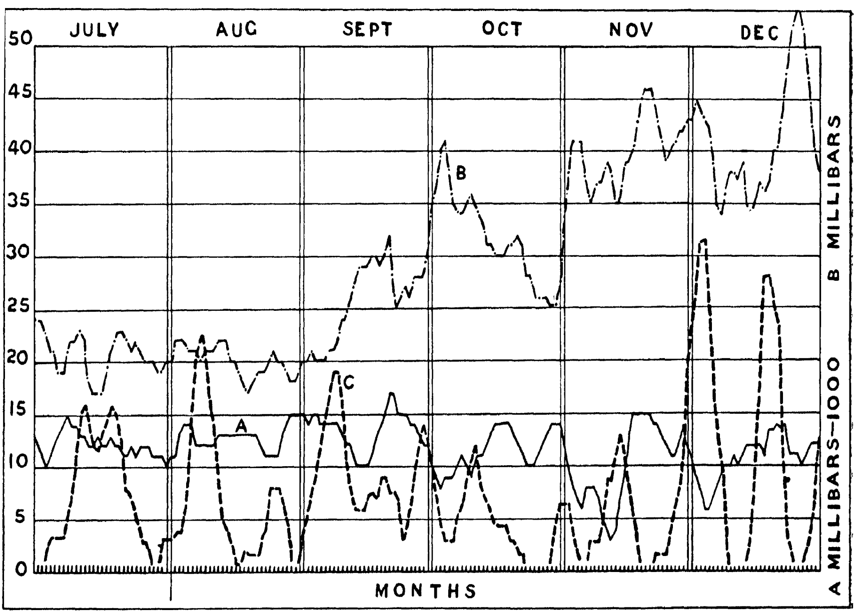




Figs. 89, 90. 1930.

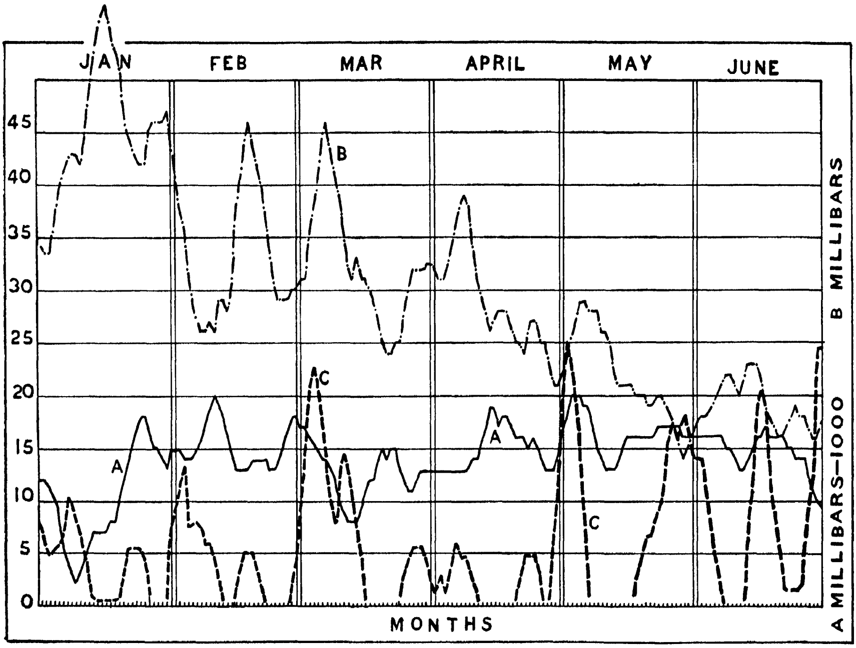
(A) Atlantic Area Mean Pressures; (B) Atlantic Area Pressure Ranges; (C) Wolf Sunspot Numbers; (D) Arctic Area Mean Pressures.

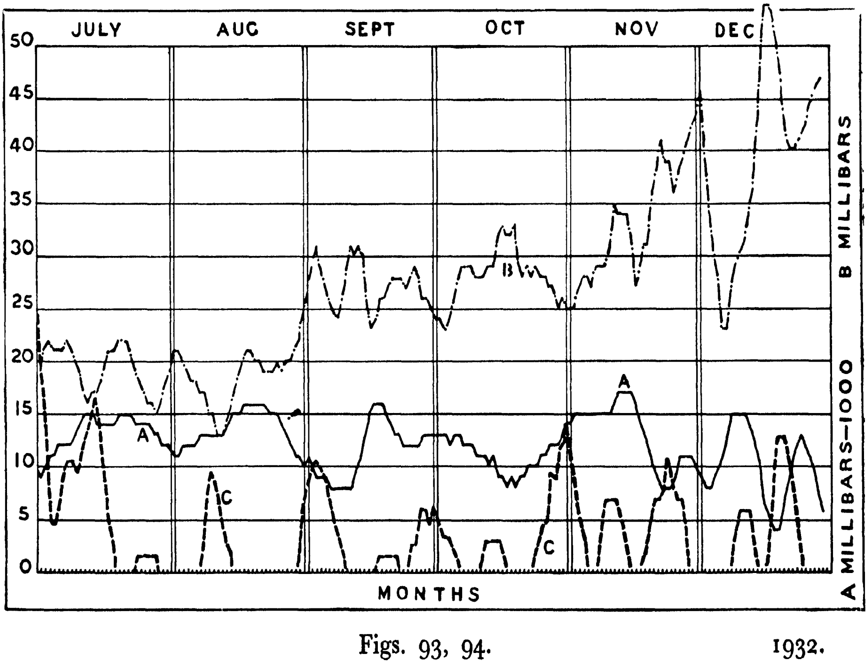




Figs. 91, 92. 1931.

(A) Atlantic Area Mean Pressures; (B) Atlantic Area Pressure Ranges; (C) Wolf Sunspot Numbers.





Figs. 93, 94. 1932.

(A) Atlantic Area Mean Pressures ; (B) Atlantic Area Pressure Ranges ; (C) Wolf Sunspot Numbers.

Table XIII shows mean monthly variations of pressure with latitude.

TABLE

Variation of Pressure

Atlantic Area,

MILLIBARS

1929.

		40°	50°	60°	70°	80° N.
WINTER MONTHS.	Jan.	15·9	13·6	16·4	16·7	23·2
	Feb.	14·8	14·3	14·8	13·1	15·2
	Mar.	16·6	15·1	10·2	6·3	13·9
	Oct.	18·3	13·7	4·4	3·1	4·5
	Nov.	17·6	10·6	4·9	6·5	13·0
	Dec.	19·0	10·7	− 0·6	− 2·0	5·4
	Means	17·1	13·0	8·5	7·3	12·5
SUMMER MONTHS.	April	14·9	13·2	12·9	15·9	21·5
	May	18·4	14·7	12·5	11·7	19·9
	June	17·0	13·9	10·2	13·9	18·8
	July	18·5	14·9	10·6	11·2	12·7
	Aug.	16·5	15·7	10·6	9·9	14·3
	Sept.	18·4	17·4	10·2	6·6	9·2
	Means	17·3	14·9	11·2	11·5	16·1

1931.

WINTER MONTHS.	Jan.	14·1	12·5	6·2	7·4	13·1
	Feb.	17·1	16·3	10·5	4·4	6·3
	Mar.	5·4	10·0	12·9	16·7	16·8
	Oct.	16·9	16·3	9·2	5·8	8·6
	Nov.	19·1	12·5	7·2	3·7	7·9
	Dec.	19·9	19·4	5·9	5·3	3·8
	Means	15·4	14·5	8·6	7·2	9·4
SUMMER MONTHS.	April	16·1	14·3	11·1	12·6	19·1
	May	13·0	10·9	12·6	17·2	17·9
	June	16·2	14·5	11·9	13·9	19·1
	July	13·8	12·6	8·9	10·4	12·3
	Aug.	15·6	12·7	12·1	10·5	10·3
	Sept.	17·2	16·1	11·7	10·3	10·3
	Means	15·3	13·5	11·4	12·5	14·8

SUMMER MEANS.

1929	17·3	14·9	11·2	11·5	16·1
1930	16·5	12·3	11·1	13·1	17·1
1931	15·3	13·5	11·4	12·5	14·8
1932	16·9	14·7	11·2	12·1	16·0
Means	16·5	13·8	11·2	12·3	16·0

XIII.
with Latitude.

1929–1932.

— 1000.

1930.

		40°	50°	60°	70°	80° N.
Winter Months.	Jan.	20·7	13·2	0·7	— 0·2	7·8
	Feb.	17·1	15·5	13·2	8·4	5·2
	Mar.	14·5	10·1	7·2	8·2	14·9
	Oct.	16·8	13·4	6·3	6·5	11·5
	Nov.	19·7	13·1	3·4	2·6	5·6
	Dec.	18·1	13·9	7·3	4·3	9·1
	Means	17·8	13·2	6·3	4·9	9·0
Summer Months.	April	14·1	11·2	13·6	15·4	20·4
	May	17·2	13·2	11·6	13·9	17·4
	June	17·9	10·5	9·9	9·8	11·7
	July	16·1	11·6	7·9	11·6	14·8
	Aug.	17·3	14·1	10·2	13·9	19·4
	Sept.	16·4	13·4	13·6	14·2	19·2
	Means	16·5	12·3	11·1	13·1	17·1

1932.

Winter Months.	Jan.	23·3	17·2	4·1	— 1·2	5·9
	Feb.	15·2	17·8	17·9	12·9	10·6
	Mar.	11·8	10·8	10·8	13·5	18·7
	Oct.	18·5	13·8	5·4	7·2	12·1
	Nov.	20·6	19·4	10·2	5·1	10·2
	Dec.	20·7	16·1	6·2	— 0·5	1·4
	Means	18·3	15·8	9·1	6·2	9·8
Summer Months.	April	16·8	13·9	11·3	14·4	22·4
	May	16·4	12·7	15·1	18·9	21·5
	June	16·6	16·1	13·8	14·2	16·2
	July	17·1	12·9	10·3	11·5	15·1
	Aug.	17·9	16·7	8·8	8·8	10·8
	Sept.	16·9	15·9	8·1	4·8	10·2
	Means	16·9	14·7	11·2	12·1	16·0

Winter Means.

	17·1	13·0	8·5	7·3	12·5
	17·8	13·2	6·3	4·9	9·0
	15·4	14·5	8·6	7·2	9·4
	18·3	15·8	9·1	6·2	9·8
Winter	17·1	14·1	8·1	6·4	10·2
Summer	16·5	13·8	11·2	12·3	16·0
Means	16·8	13·9	9·6	9·3	13·1

A number of the daily charts will now be figured. The charts, as published, were sufficiently complete to enable the isobars to be extended over the Arctic Ocean, and full responsibility is taken by the present author for the accuracy of the additions which have been made to the originals.

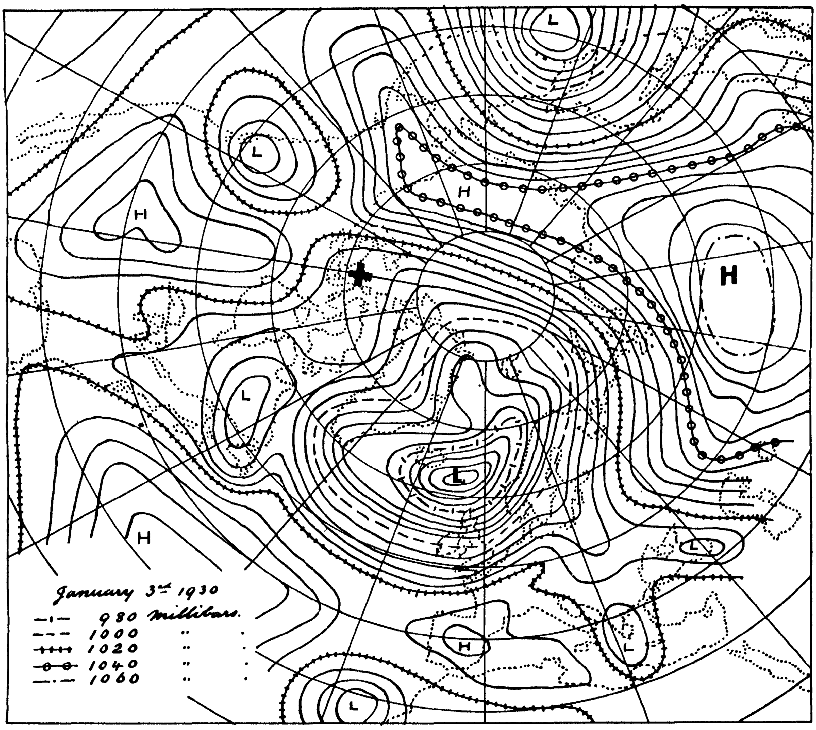
According to Sir John Moore, who compared the highest with the lowest pressure he had ever read in Dublin, the greatest difference of pressure (taken on different dates) was 110 mbs., whilst the highest pressure known to him was at Semipalatinsk in Siberia in 1877, and the lowest at Orissa in 1885, the range being about 156 mbs. These are very striking figures and make it clear how greatly the weight of the atmosphere varies from time to time owing to temperature differences.

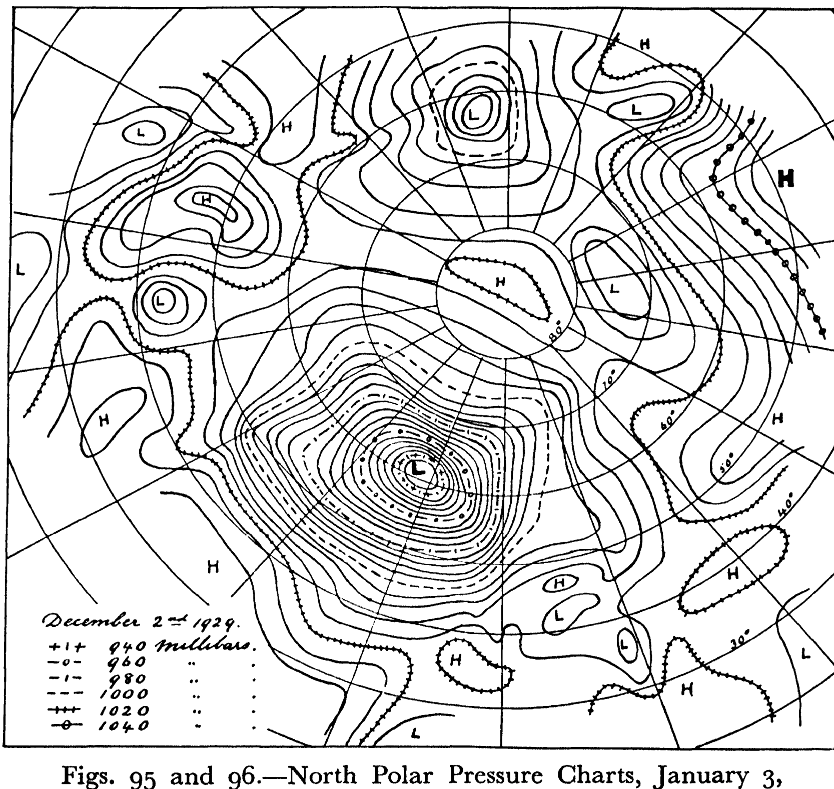
A few instances of great temperature and pressure differences, as illustrated by the Charts, will now be given.

The distribution of atmospheric pressure over the North Polar area for 3rd January, 1930, is shown in Fig. 95. At about 80° E. longitude and latitude 55° N., over Siberia, the temperature was below −33° F., and the pressure exceeded 1060 mbs., whilst at the same moment over the Faroes the temperature was 39° F. and the pressure as low as 964 mbs., a range of 96 mbs. Both these localities were at the time receiving little light and heat from the sun. Fig. 95 also shows that over the Pacific there was a cyclone, whose centre was below 986 mbs., whilst over Central North America the temperature was −32° F. and the pressure exceeded 1036 mbs. From Alaska across the Arctic Ocean there extended a high-pressure ridge. The cross on the charts is over the magnetic pole.

An equally remarkable instance of extremes of pressure in the Northern Hemisphere occurred on 2nd December, 1929, as will be seen from Fig. 96. Near Iceland the temperature was 46° F. and the pressure was down to 936 mbs., whilst over Siberia the temperature was −15° F. and the pressure higher than 1048 mbs., a pressure range of 112 mbs. At this time a pressure ridge also crossed the Arctic Ocean from Asia to America. The Atlantic cyclone was much deeper than that over the Pacific.

Under the conditions of pressure shown in Fig. 95 the differences between the temperatures of the two columns of air must have been about 10 per cent. of the absolute temperature, *i.e.* about 45° F., whereas the surface temperature difference was 72° F. Now it is clear that if this actual surface temperature difference continued to be





Figs. 95 and 96.—North Polar Pressure Charts, January 3, 1930, and December 2, 1929.

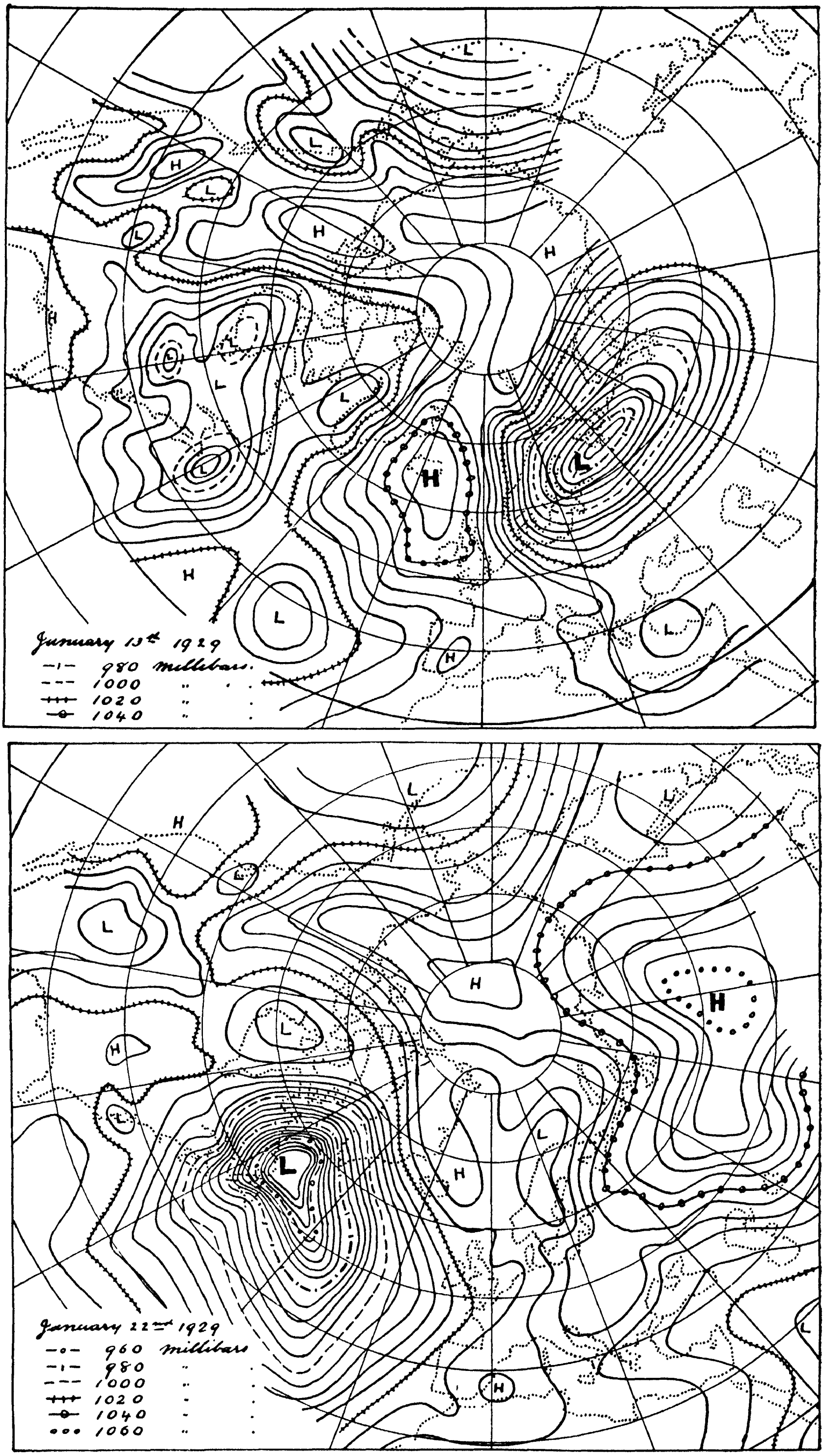
effective up to the top of the atmosphere it would have been more than sufficient to account for the difference of pressure. However, as we shall see, there are good reasons for believing that surface temperatures do not extend upwards in this manner, the great changes in the pressure gradients and mean temperatures between one locality and another not being dependent upon surface conditions. That this is the case can be demonstrated by taking the phenomena shown by certain cyclones over the land in winter which have not drifted into the positions they occupy, and contemporaneous anticyclones over the sea.

Such a case was that of 13th January, 1929 (Fig. 97), for the disturbances were in much the same positions on January 7th, the lowest pressure then being only 1000 mbs. On January 12th the pressure over Russia was 996 mbs. and the temperature $-38°$ F., whereas the pressure over northern Scotland was 1044 mbs. and the temperature 25° F. Here we have the ground temperature over the centre of the cyclone 63° F. lower than it was over the anticyclone.

During winter the oceanic areas are generally warmer near the surface of the earth than are the continental areas; but during the summer the reverse is the case. On this account it might seem reasonable to expect that, during the winter, cyclones would tend to form only over the warm oceans. However this is not always the case, as will be seen from Fig. 97, which shows that the pressure conditions for 13th January, 1929, were high over the Atlantic Ocean and low over the White Sea in Russia. Indeed during this month the continents and oceans do not seem to have largely controlled the pressure conditions.

Such deep depressions as the one that existed over Russia from January 7th till January 13th, 1929 (Fig. 97), are much more common than is supposed. Their size and depth make it impossible for them to be the result of local heating near the earth's surface over the areas they cover; and they are often formed during the polar nights. To produce them the atmosphere must be locally heated at great heights above the elevations reached by our mountain ranges. It is this heating of the upper troposphere and stratosphere that lowers the tropopause over cyclones.

On 22nd January, 1929, the conditions were as shown in Fig. 98, viz. pressures were high east of the meridian of Greenwich (1060 mbs.) and low over Eastern North America and the West Atlantic, almost a reversal of the conditions shown in Fig. 97. Pressure in the cyclone over



Figs. 97 and 98.—North Polar Pressure Charts, January 13 and 22, 1929.

Eastern America on 22nd January, 1929, was below 948 mbs., the centre of the cyclone being over Baffin Bay, whereas the same day, to the east of Greenwich, over Siberia, the pressure was 1060 mbs.

January, 1929, was thus a very interesting month. To illustrate the high-pressure conditions, the *mean* pressure chart, Fig. 99, for January, 1929, is given. Pressure was generally high over the whole of Europe, Northern Asia, Iceland, Northern Greenland and the Arctic Ocean, and

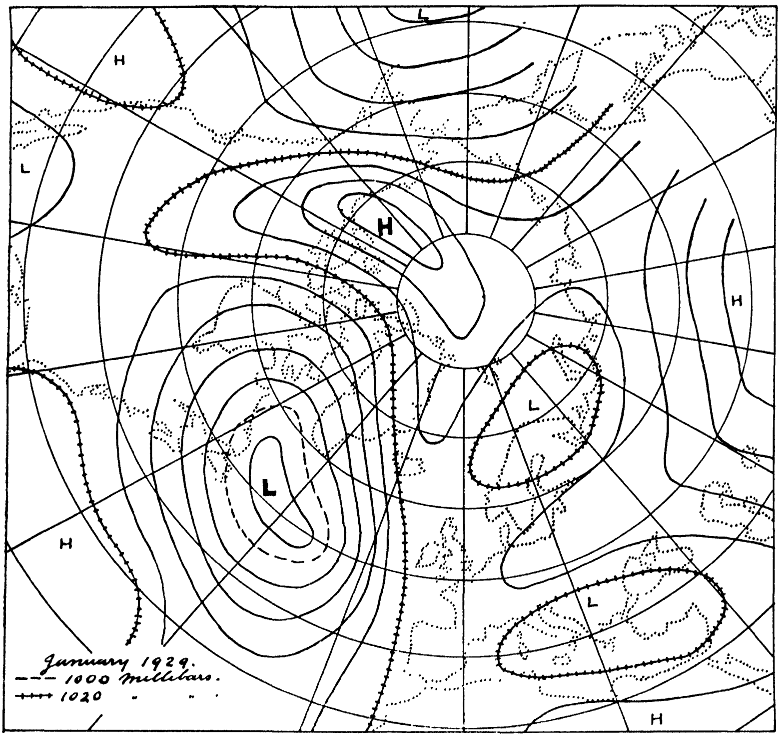


Fig. 99.—Mean North Polar Pressure Chart, January, 1929.

low off the coast of Labrador and in the North Pacific. From Europe to Asia a high-pressure ridge crossed the Arctic Ocean and passed down the Rocky Mountains of North America.

Another chart of considerable interest is that for 7th January, 1929 (Fig. 100). Here there is a wedge of high pressure extending from the Black Sea across Scandinavia to North Greenland, beyond which it passed down Central North America along 100° W. longitude.

We will now consider October, 1929, also a winter month, during which the pressures were low in the extreme

north. As an illustration of how the low-pressure conditions persisted, charts for 3rd October, 1929 (Fig. 101), and for 31st October, 1929 (Fig. 102), are given. Here (Fig. 102) the low pressures were centred over Greenland and Kamchatka, the high pressures being over Southern Europe, Asia and Central North America. For comparison with the high mean pressure conditions of January, 1929 (Fig. 99), the mean pressure chart for October, 1929 (Fig. 103), when the pressures were low, has been drawn.

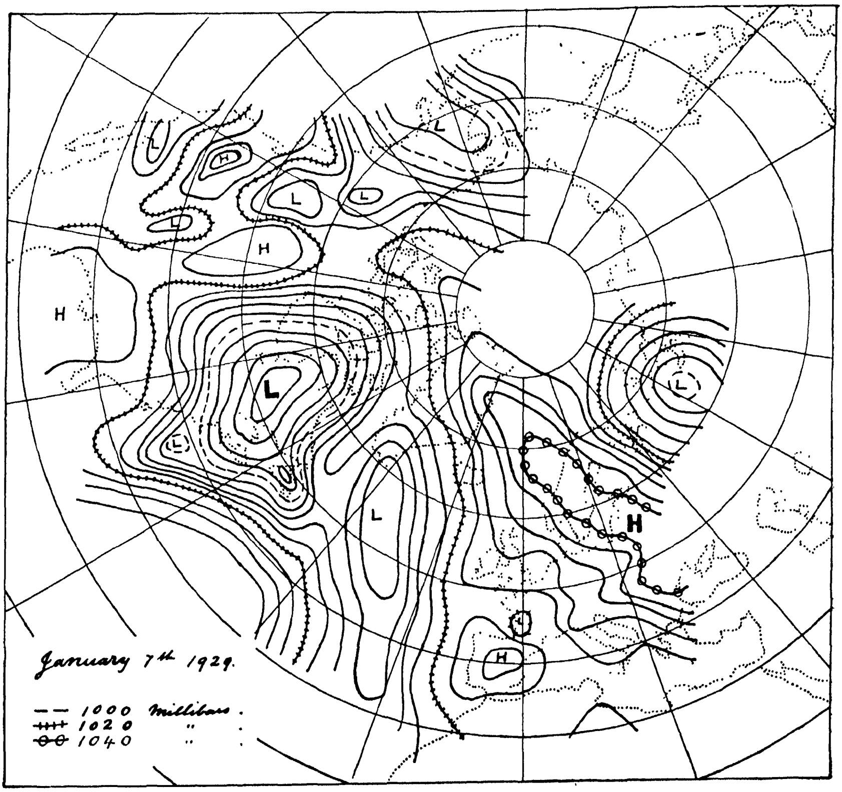
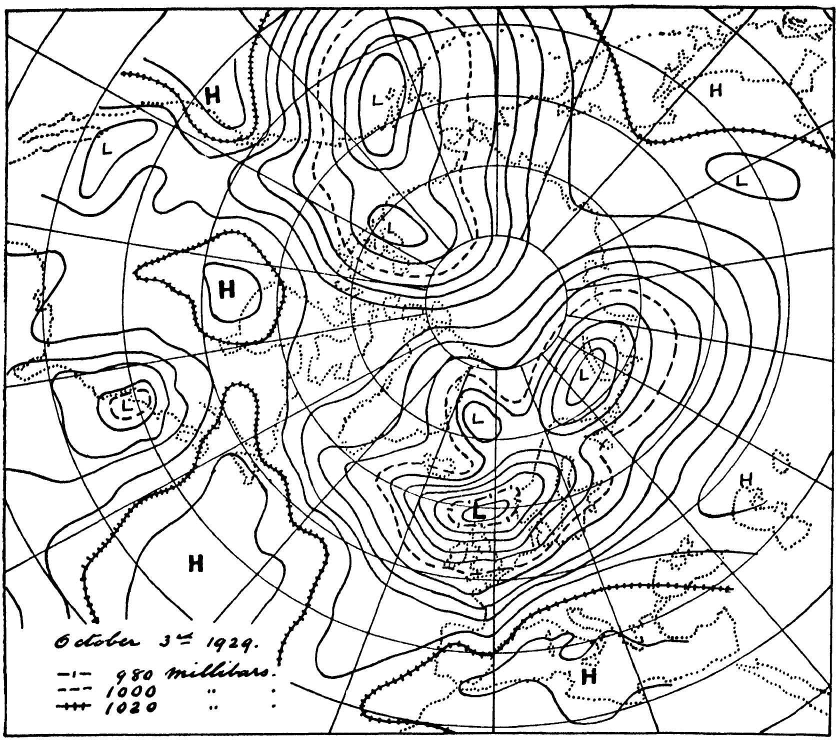
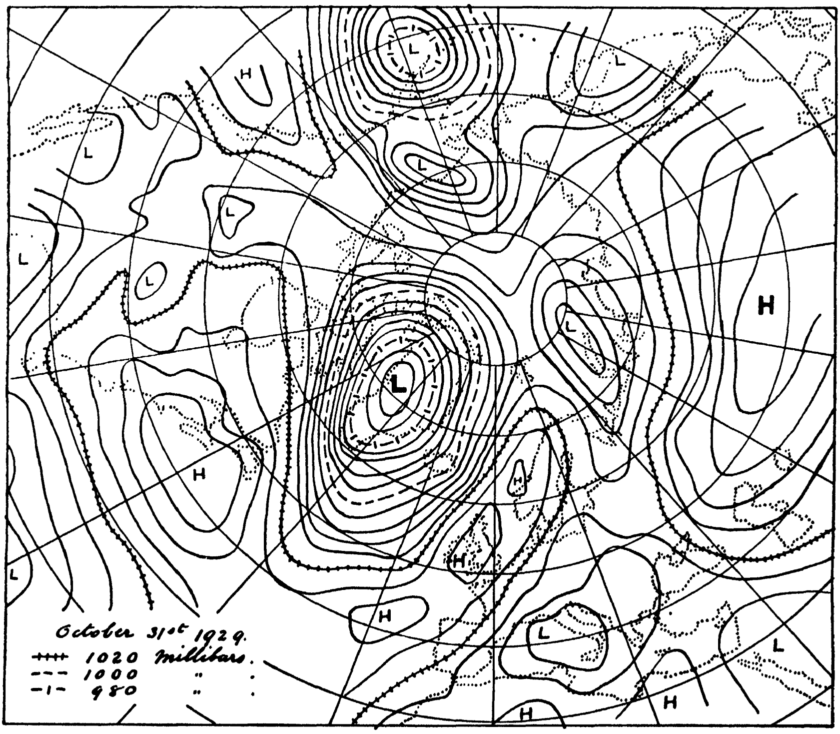


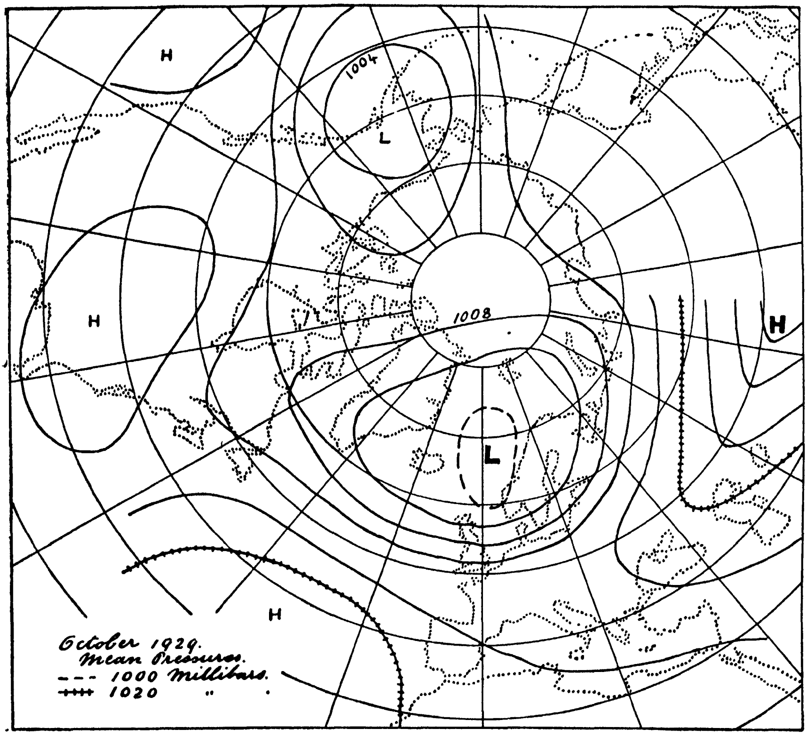
Fig. 100.—North Polar Pressure Chart, January 7th, 1929.

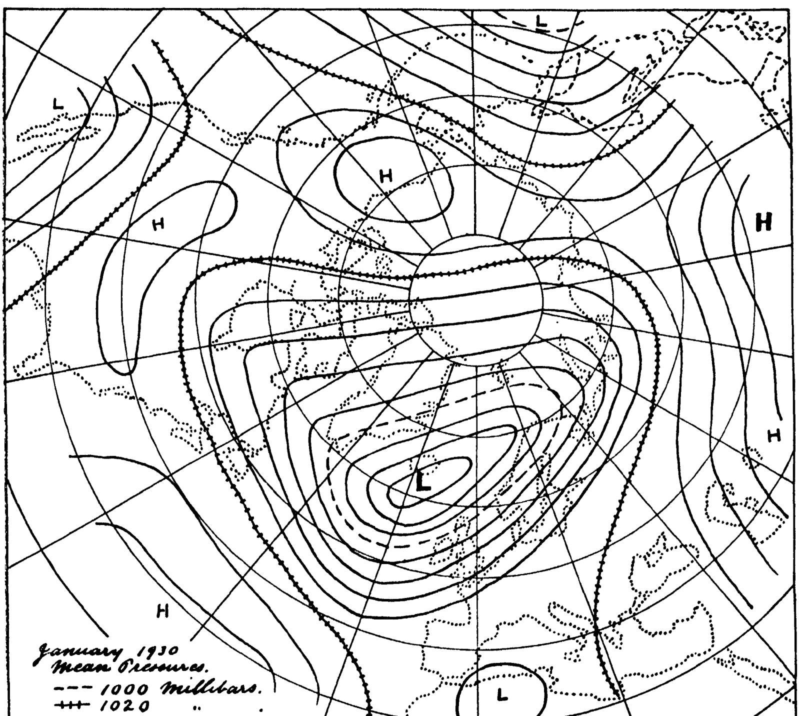
For the first six months of 1930 charts giving the monthly mean pressures have also been drawn, as also have charts exhibiting daily pressure conditions for the same interval. The mean pressure charts show that during the winter the pressures were low over Iceland and the North Pacific, a ridge of moderately high pressure extending across the Arctic Ocean from Asia to America. During the summer the low-pressure area almost filled up, the polar high-pressure ridge being of a more pronounced character. These charts are shown in Figs. 104 to 120.



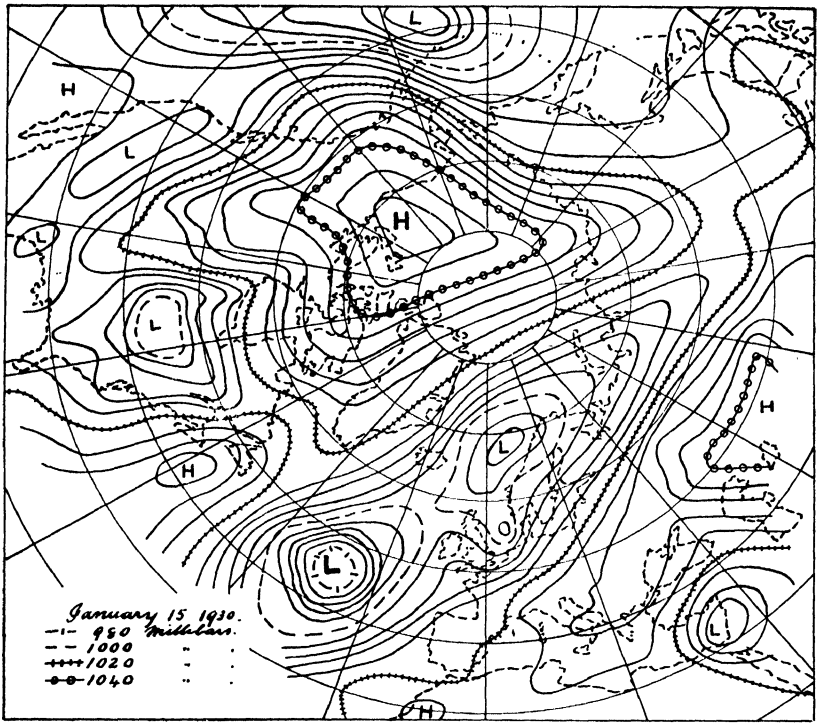


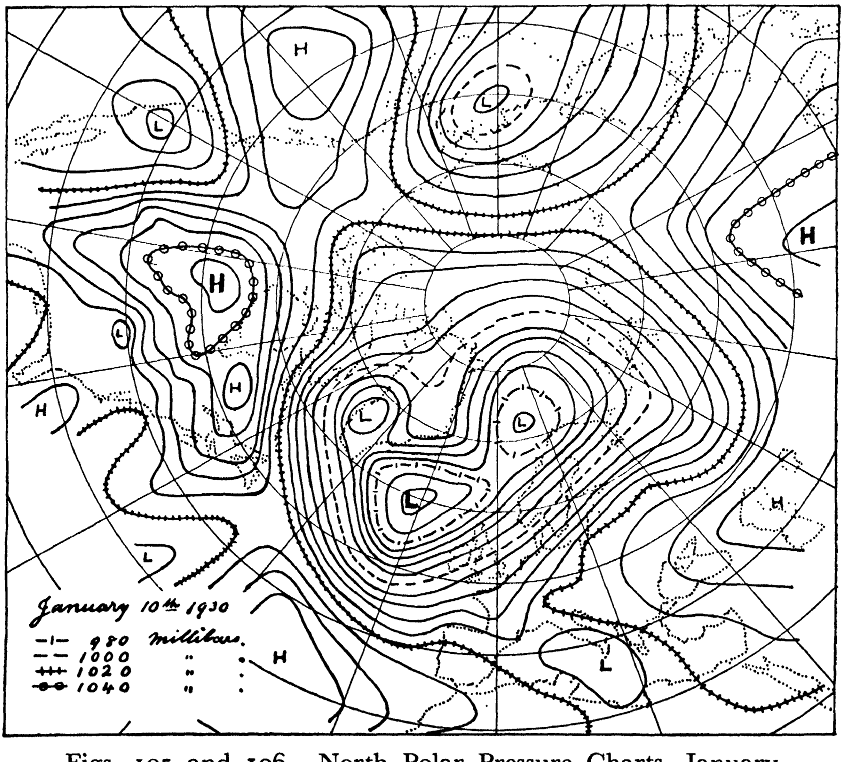
Figs. 101 and 102.—North Polar Pressure Charts, October 3 and 31, 1929.





Figs. 103 and 104.—Mean North Polar Pressure Charts, October, 1929, and January, 1930.





Figs. 105 and 106.—North Polar Pressure Charts, January 15 and 10, 1930.

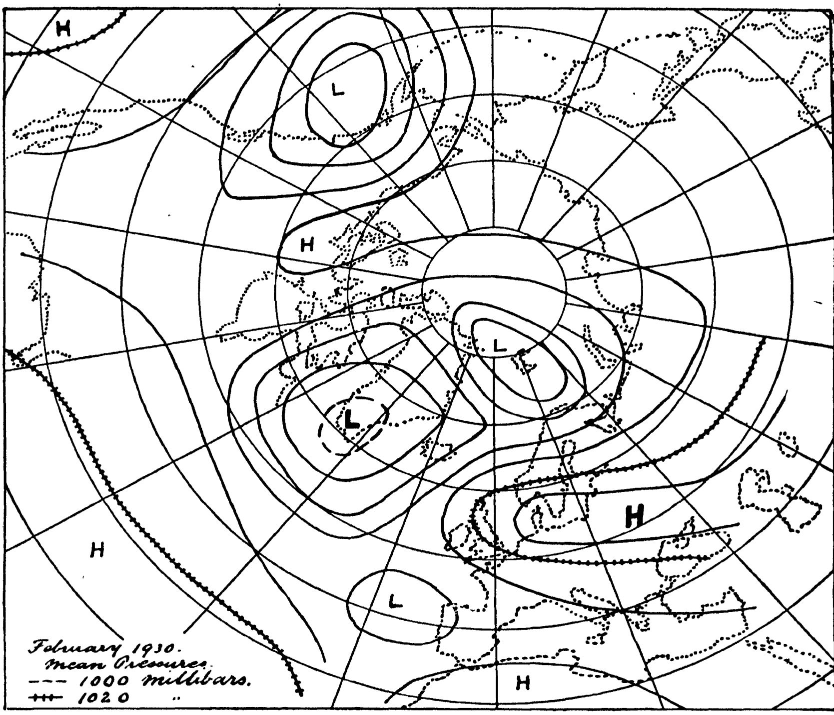


Fig. 107.—Mean North Polar Pressure Chart, February, 1930.

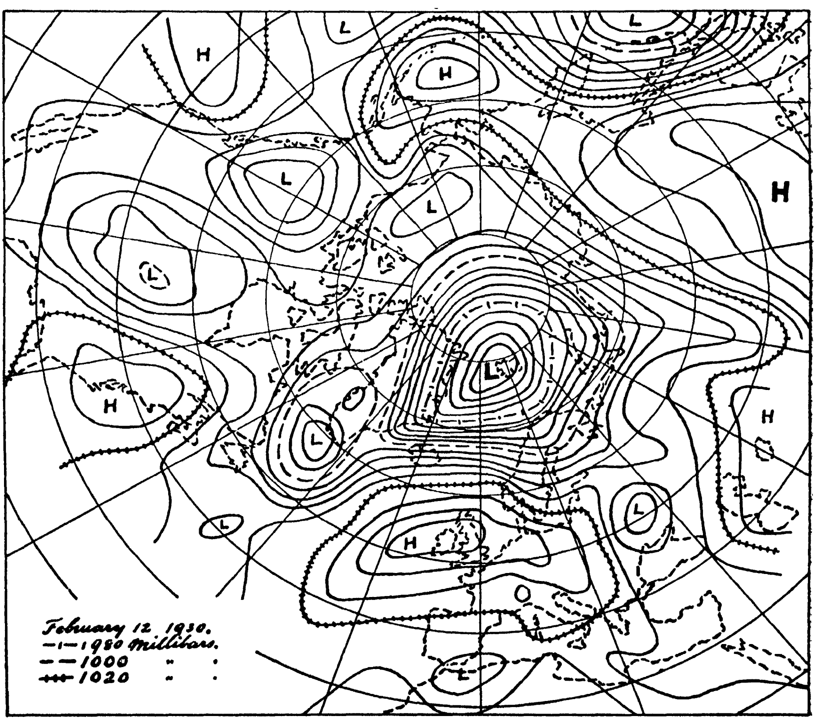


Fig. 108.—North Polar Pressure Chart, February 12, 1930.

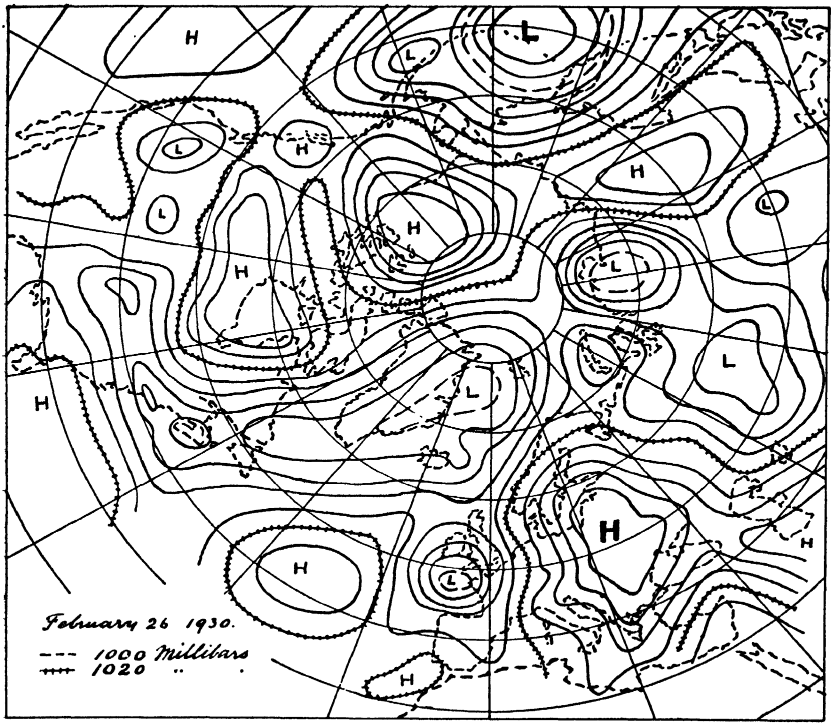


Fig. 109.—North Polar Pressure Chart, February 26, 1930.

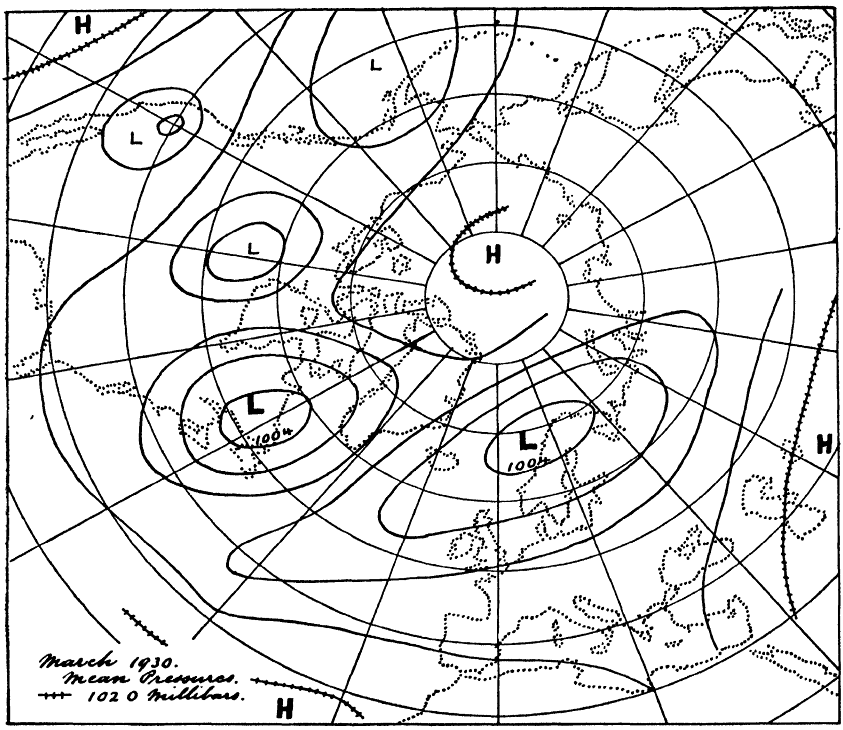
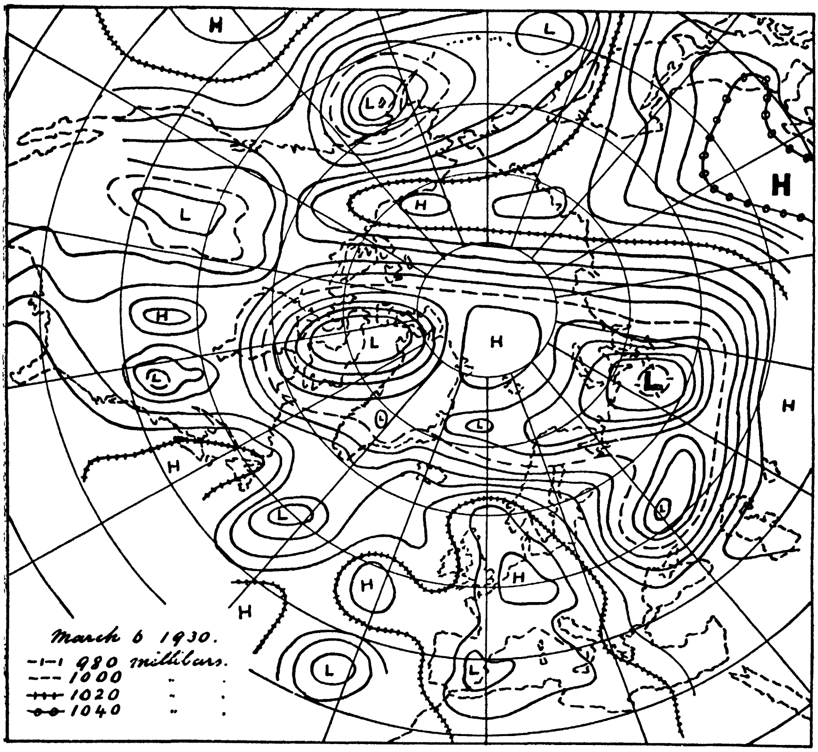
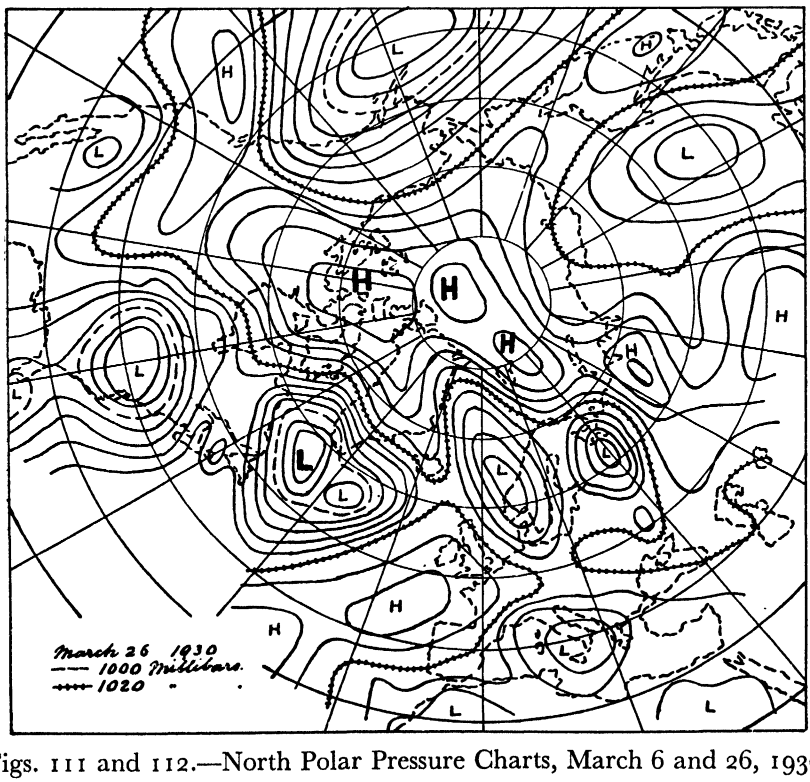


Fig. 110.—Mean North Polar Pressure Chart, March, 1930.





Figs. 111 and 112.—North Polar Pressure Charts, March 6 and 26, 1930.

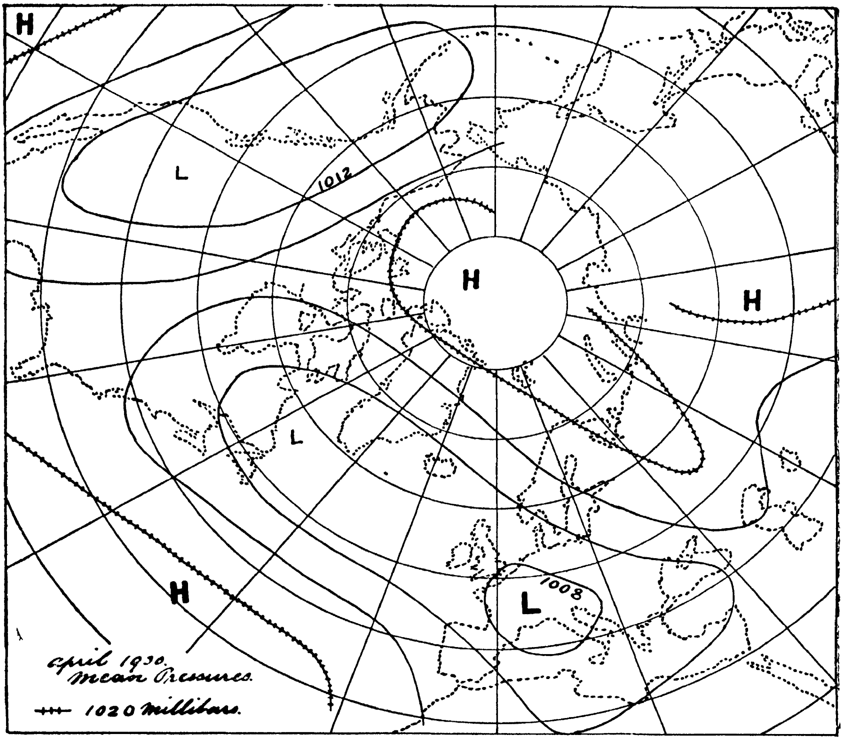


Fig. 113.—Mean North Polar Pressure Chart, April, 1930.

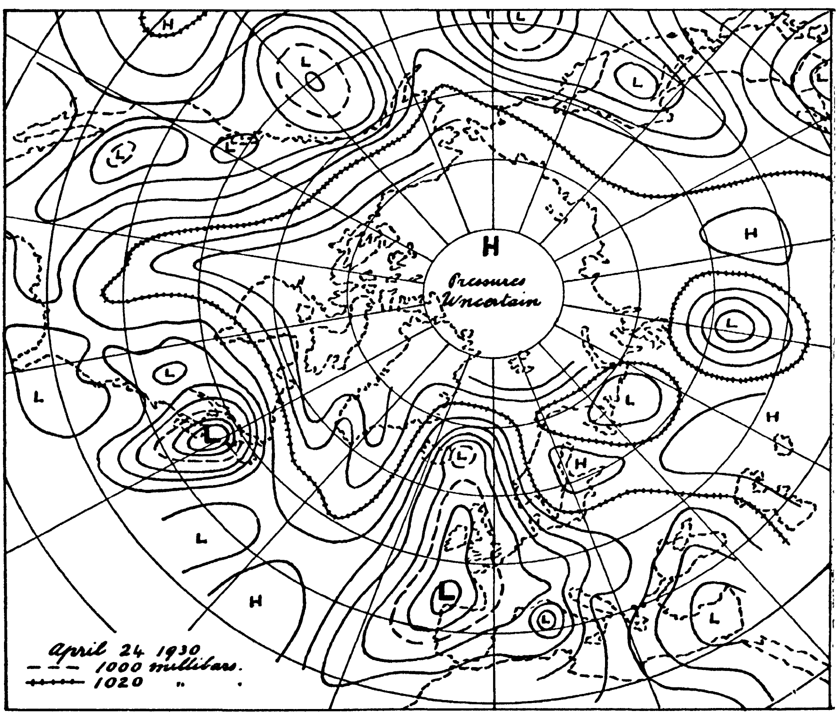


Fig. 114.—North Polar Pressure Chart, April 24, 1930.

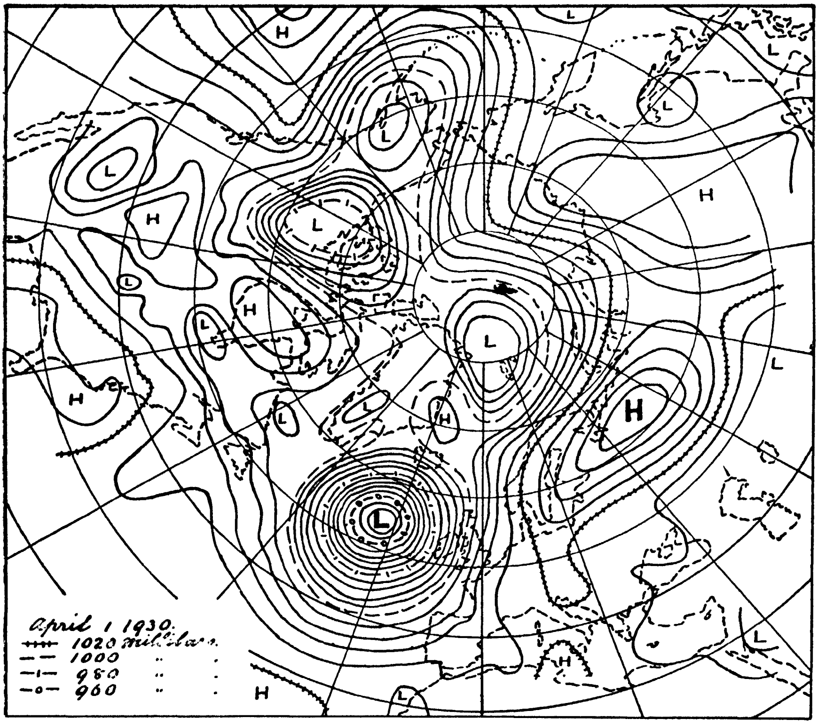


Fig. 115.—North Polar Pressure Chart, April 1, 1930.

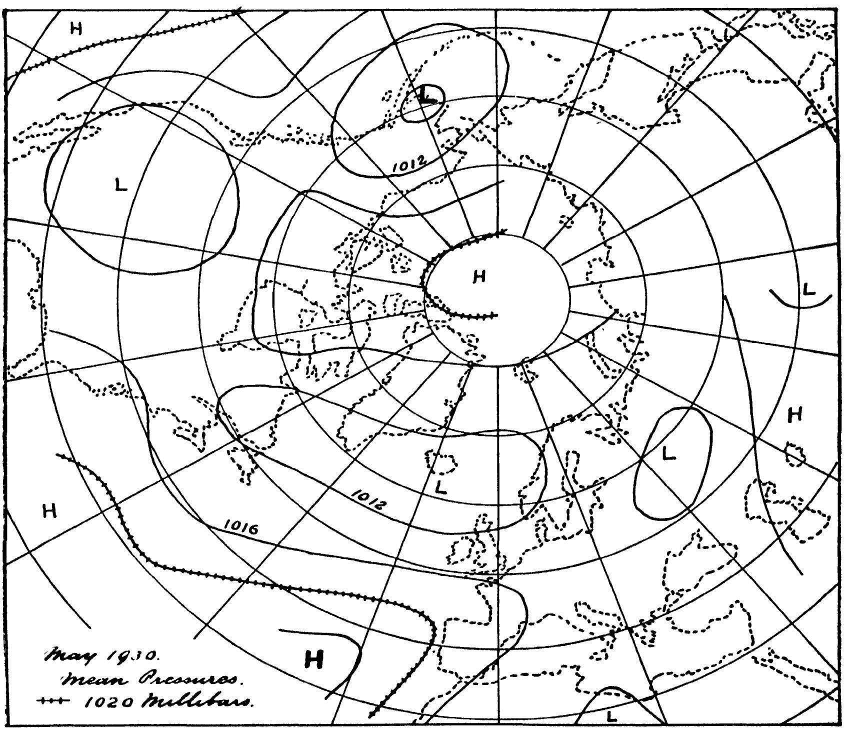
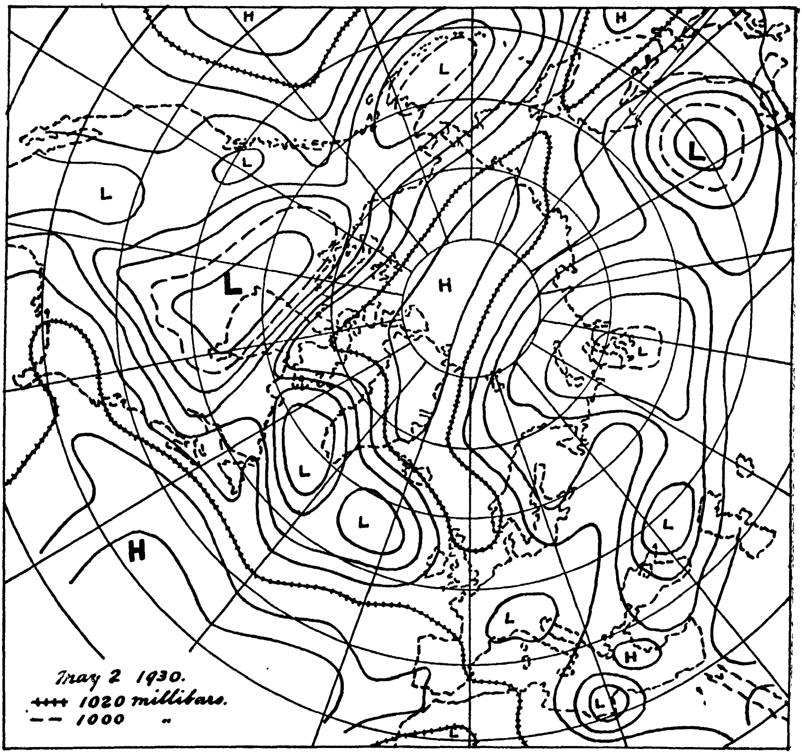
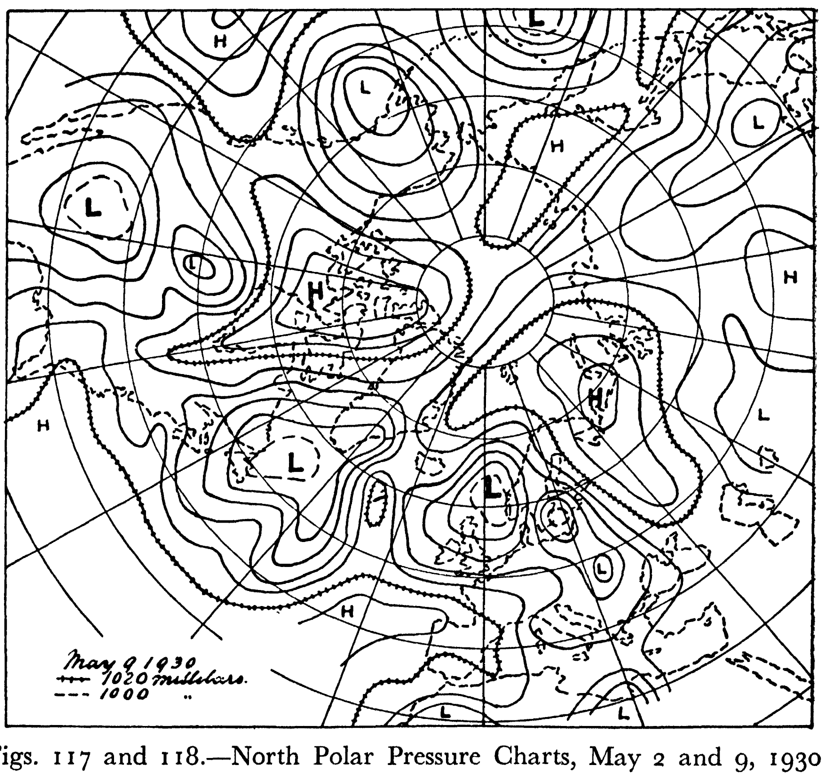


Fig. 116.—Mean North Polar Pressure Chart, May, 1930.





Figs. 117 and 118.—North Polar Pressure Charts, May 2 and 9, 1930.

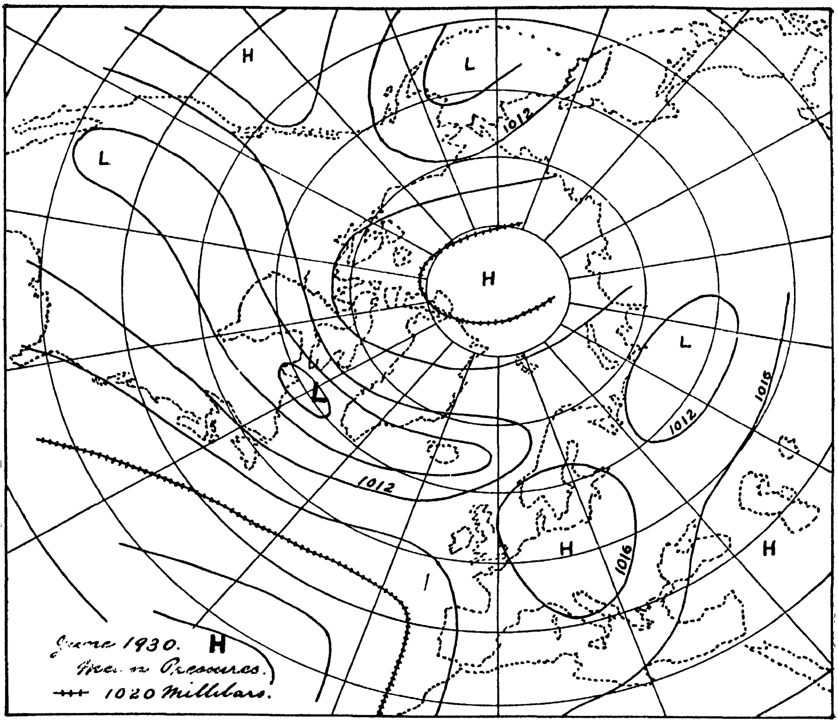


Fig. 119.—Mean North Polar Pressure Chart, June, 1930.

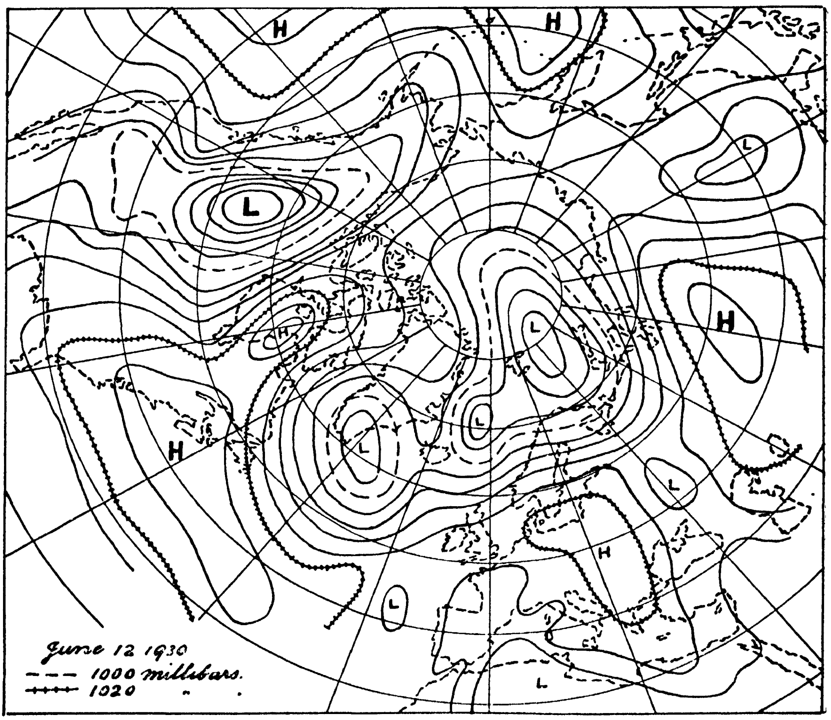


Fig. 120.—North Polar Pressure Chart, June 12, 1930.

All the charts have been selected to show types of pressures. They are not selected to show rare conditions. It is a striking fact that Greenland does not appear to influence pressures in any marked way, for there is no instance during the four years of a typical anticyclone existing over this area—in a few cases, however, such conditions do extend from other areas over it. Still there is little doubt but that when cyclones do not disturb the air much, a cold layer of air forms over Greenland and moves outwards towards the sea, but scarcely affects the pressure conditions.

It might be gathered from a cursory view of the daily synchronous charts which have been illustrated, that pressure changes in high latitudes are quite irregular. The same may be said of the variations of pressure with latitude. On the contrary, however, we shall see that although great and very irregular changes do occur all the year round, there are still regular seasonal and other changes of a very interesting character.

It is an interesting and important fact that as the North Pole is approached the mean daily oscillation of pressure from day to day becomes greater, especially during the winter. In Fig. 121 the ordinates are mean pressures along lines of latitude and the abscissae days. The figures are for the first six months of 1930. It will be noticed that the pressure changes which occur from day to day, and therefore the pressure ranges, are small along latitude 30° N., but grow more and more pronounced as higher and higher latitudes are reached. It will also be seen that the changes are periodic in character, some of the periods, or waves of pressure variation, having a duration of as long as one month. These variations are largely due to the development of cyclones, and these cyclones become larger and deeper as higher latitudes are reached. However, there are also, it would appear, changes in the mean pressure which affect cyclones and anticyclones as well. In other words, the formation of a cyclone is a local feature, resulting from local heating of the atmosphere above it.

It will be remembered that all the barometric readings used to construct the daily weather charts are corrected for height above sea-level, and that in consequence the actual barometric readings taken are often largely increased for the purpose of drawing the daily weather maps. However, in spite of the addition of the weight of a great thickness of air (the calculated weight of the air below the barometer) the corrected pressures do not have the effect of obliterating,

or even very appreciably affecting, the pressure gradients in cyclones and anticyclones, for the corrected isobars pass from the lowlands over hilly country without appreciable distortion, and we must assume that cyclones are not due to density gradients at low levels. Indeed all systematic observations concerning the anatomy of cyclones show that, below the levels reached by our mountain ranges, density

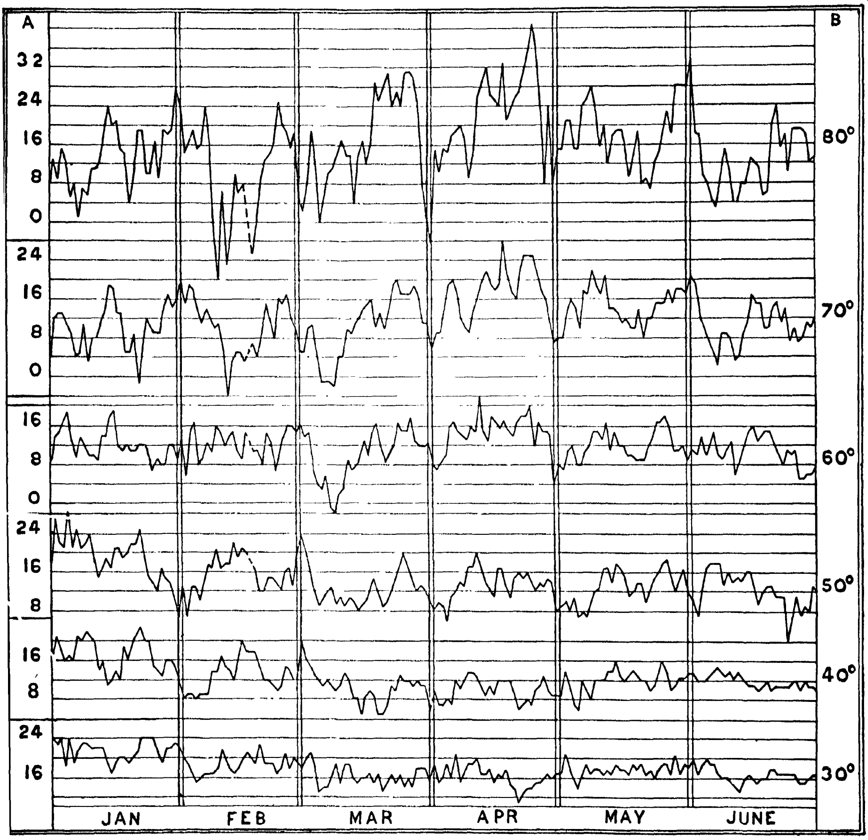


Fig. 121.—Daily Pressure Variations with Latitude, 1930.

gradients due to temperature variations are generally slightly opposed to, rather than in favour of, the air movements that actually take place.

If the atmospheric upper limit be normally approximately at the same distance from the earth's surface everywhere, the great differences of pressure between cyclones and anticyclones must result from local high temperatures affecting the atmosphere at somewhat higher levels than our mountain ranges reach, for at very high levels the air, even if considerably warmed, could not give rise to very great

pressure differences owing to its tenuity. It is also clear that the heated mass of air must be above the centre of the low-pressure area. That such local high-temperature conditions should exist at high levels, even in very high latitudes during the long winter nights, is very remarkable.

Many meteorologists are disinclined to believe that the variable fall of pressure which takes place as the poles are approached from lower latitudes is due to a continuous rise in the temperature of the atmosphere as a whole. Indeed what are called "dynamical," rather than "thermal," agencies are called upon to account for the facts ; but no clear detailed explanation of the hypothesis is ever given. The problem cannot be discussed here, but in a subsequent chapter it will be considered at some length. However it can be seen clearly from the pressure gradients shown by the isobars on the charts that have been figured that the warm air does not force its way in a northerly direction against the more dense cold air. It flows down the pressure gradients, and the resulting winds obey the law of Buys Ballot. Still the flow is contrary to the surface temperature gradient, and it is clear that this temperature gradient must be reversed at considerable heights above the ground to account for the magnitude of the surface isobars.

One of the most interesting points in connection with the new daily weather charts is that they enable us to ascertain how pressures vary with latitude during the seasons. In Table XIII the monthly figures showing this for the Atlantic Area during the years 1929–1932 are given. It will be noticed that for latitudes 40° and 50° the winter mean pressures are higher than the summer ones, whereas for 60°, 70° and 80° the reverse is the case. The table also shows that for latitudes 60° and 70° the pressures are lower than they are both to the north and south.

From a theoretical point of view these varying changes of pressure with latitude are of very great interest, especially as they sometimes give to high latitudes an anticyclonic character, in place of the cyclonic conditions which generally prevail there.

Table XIII does not bring out this feature quite as clearly as does an examination of synchronous charts, for during most months there are high- as well as low-pressure intervals of time, and the means then very often obscure features of considerable interest.

To show the great differences of pressure with latitude when periods of high and low pressure are contrasted, Table XIV has been drawn up. The area selected was

that covered by the daily weather charts, omitting the East Siberian quadrant. Thirty days when the pressure was highest and thirty-three when the pressures were lowest were taken during the period covered by the first six months of 1930, and from these figures the mean pressures for latitudes 40°, 50°, 60°, 70° and 80° N. were calculated.

TABLE XIV.

Differences of Pressure with Latitude.

WHOLE AREA.

Latitude . .	30°	40°	50°	60°	70°	80°
Low Pressure .	18·9	18·5	15·6	8·7	4·9	6·0
High Pressure .	17·0	14·7	14·5	16·0	20·3	27·7

Pressures are in Millibars less 1000.

The figures given in Tables XIII and XIV are plotted on Fig. 122. It will be seen from curve *A* that for thirty

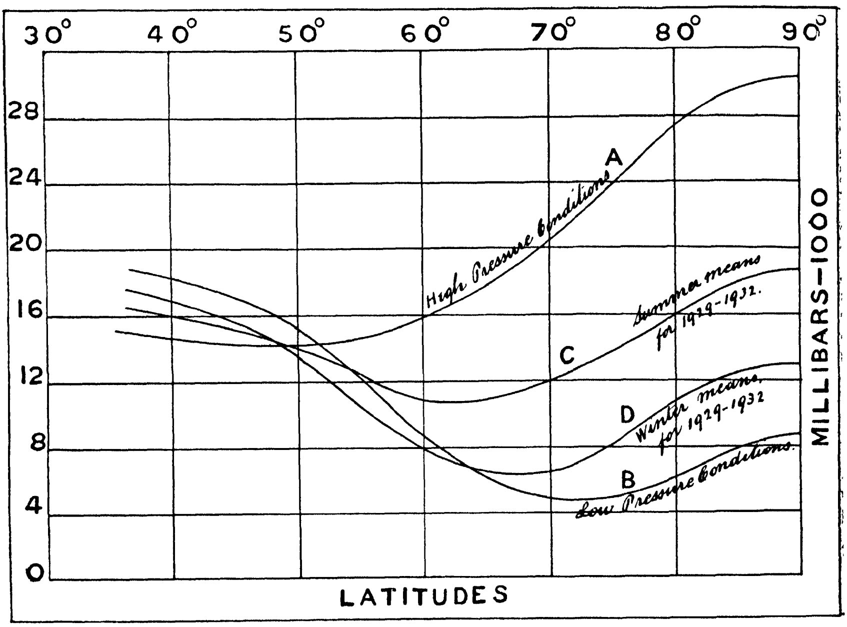


Fig. 122.—Showing Mean Pressure Variations with Latitude.

days of the first six months of 1930 the Arctic regions had anticyclonic conditions, and that the pressures favoured cold north-easterly winds, which would chill middle latitudes, but that during the thirty-three days shown by curve *B*

cyclonic conditions prevailed over high latitudes, these favouring warm south-westerly winds which would produce warm conditions over the Arctic Ocean. Curves *C* and *D* represent the pressure variation in Table XIII.

The two charts Figs. 123 and 124 illustrate the nature of the pressure distributions which are obtained by constructing mean charts from the 30 synchronous charts which give curve *A* and the 33 synchronous charts which give curve *B* (Fig. 122).

On the low-pressure chart (Fig. 124) a low-pressure area

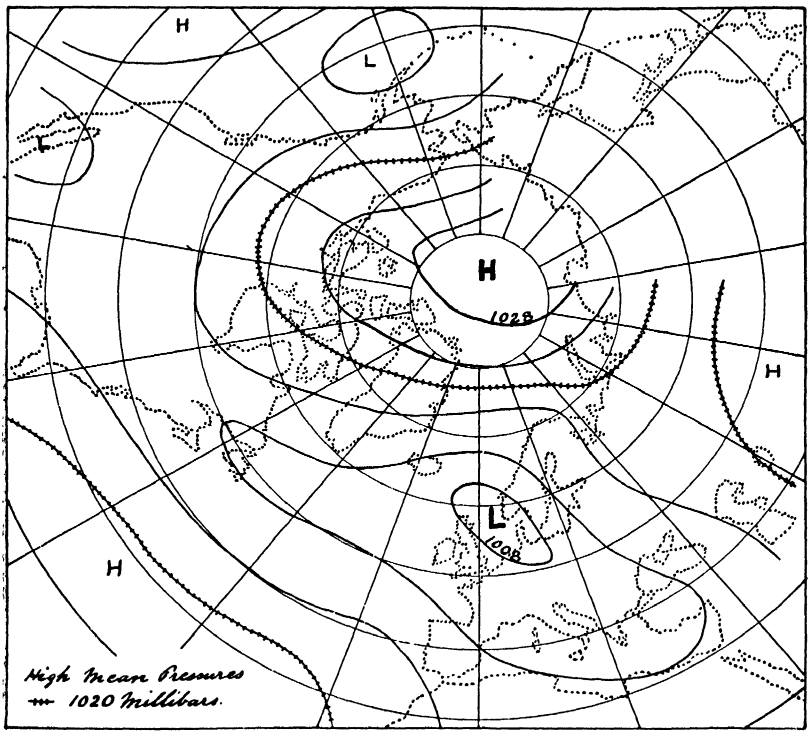


Fig. 123.—North Polar Mean High Pressure Chart.

lies over Southern Alaska and a deeper cyclonic centre lies to the north-west of Scandinavia, the two low-pressure areas being separated by a ridge the pressure along which is less than 1013 mbs. Indeed the area north of latitude 45° is a well-marked cyclone with two areas of low pressure. In the case of the high-pressure chart (Fig. 123), the two low-pressure areas are very shallow and are separated by an anticyclonic area the pressure at the centre of which exceeds 1028 mbs. Nearly all the daily synchronous charts we have figured approximate more or less to one of these two types of pressure distributions.

It has already been pointed out that the radiations from the sun which heat the atmosphere irregularly, and produce density gradients which give rise to the circulation of the atmosphere, are probably of two kinds:—

I. The light and heat rays of the sun, to which the principal heating effect in low latitudes is due, but which would be unable to prevent the rise of pressure in high latitudes shown in Fig. 123.

II. Particles, radiated from the sun, which are electrically charged, and owing to the strength of the earth's magnetic

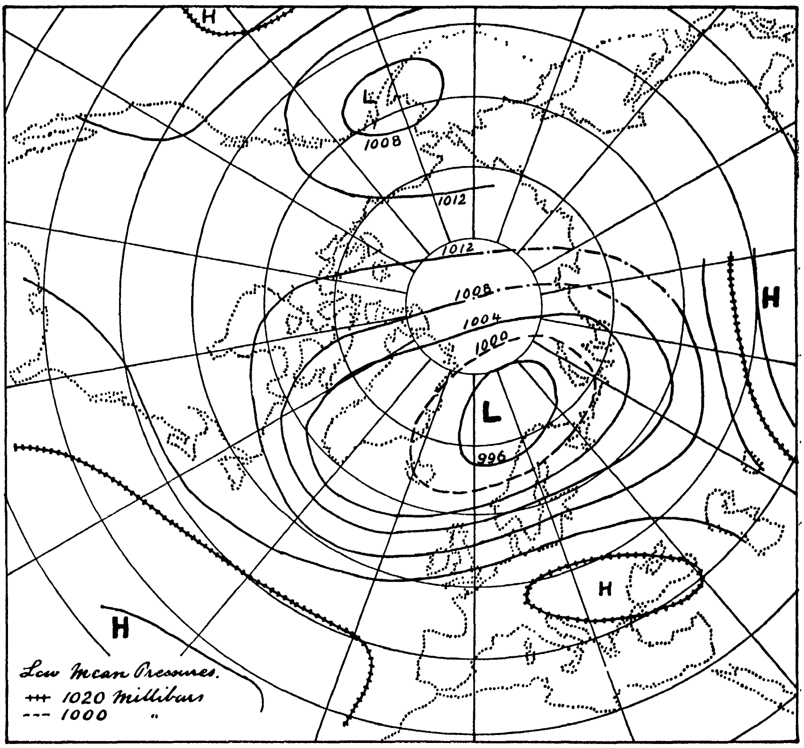


Fig. 124.—North Polar Mean Low Pressure Chart.

field are diverted towards the magnetic poles, entering the atmosphere mainly in high latitudes, where they give rise to the aurora. These may be considered, for reasons which cannot be discussed in this chapter, as having very considerable heating power.

There are two ways of regarding atmospheric pressures. One is to compare the actual mean pressures of particular areas day by day, and the other to ascertain the range of pressure, also day by day. Both these methods of analysis have been considered.

Table XV shows the mean monthly Atlantic Area pressures for the years 1929 to 1932 inclusive. For these years it will be seen that in each case the pressures were highest during the summer months and lowest during the winter months. The table also gives the mean monthly pressures of the area calculated from the Challenger Expedition Reports.

TABLE XV.

Mean Monthly Atlantic Area Pressures, 1929–32.

	Jan.	Feb.	March.	April.	May.	June.
1929 . .	16·6	14·2	12·5	14·9	15·6	14·5
1930 . .	8·5	10·7	10·7	14·4	14·3	12·8
1931 . .	10·7	12·5	12·5	14·4	15·1	14·6
1932 . .	10·2	12·5	12·5	14·9	16·4	14·7
Means . .	11·5	12·5	12·0	14·6	15·4	14·2
Challenger .	10·8	9·4	12·6	14·4	13·0	14·5

	July.	Aug.	Sept.	Oct.	Nov.	Dec.
1929 . .	13·5	13·1	12·7	9·5	9·5	6·7
1930 . .	12·1	14·3	15·6	10·8	8·7	10·7
1931 . .	13·1	12·6	13·3	11·5	10·2	10·8
1932 . .	13·1	13·6	11·6	11·2	13·1	9·8
Means . .	12·9	13·4	13·3	10·7	10·4	9·5
Challenger .	13·0	13·0	12·6	12·6	12·5	12·5

Pressures in Millibars less 1000.

It is satisfactory to note that there is on the whole a very close agreement between the figures obtained from the Challenger Monthly Pressure Charts and those from the daily weather reports.

On Fig. 125 the monthly means of the Atlantic Area pressures have been plotted. The highest was in May and

the lowest in December, the summer excess over the winter being 5·9 millibars.

During the winter, inside the Arctic Circle, quite a considerable thickness of the cold denser lower atmosphere is at a very low temperature, the range at the earth's surface between summer and winter being about 70° F. But in spite of this we find that the summer pressure is higher than that during the winter. It must be remembered that the Atlantic Area covers more land than water, and that on this account there is no reason to believe that the conditions are due to water surface temperature conditions.

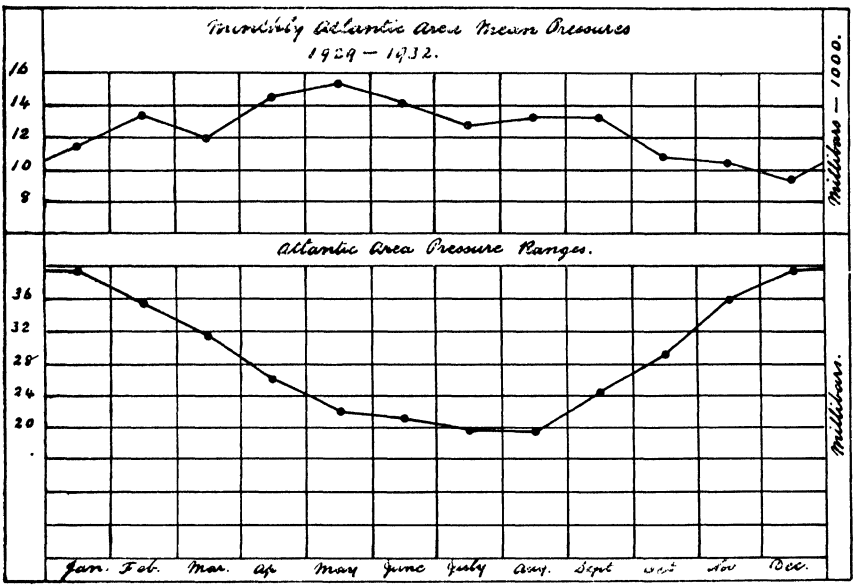


Fig. 125.—Monthly Atlantic Area Mean Pressures and Pressure Ranges, 1929–32.

It is interesting to note that the area of lowest pressure is generally to the east of the magnetic pole, which is shown on the chart Fig. 95 by an X. On the Pacific side the pressure is not so low as on the Atlantic side, and this is the case in spite of the fact that the Pacific is much more open in high latitudes than is the Atlantic Ocean.

The comparatively rapid changes of pressure shown by the mean pressure curves of Figs. 87 to 94 are accompanied by changes in the directions of the winds, and often by rapid changes of temperature. The wind directions at any moment can be ascertained from the daily charts by applying Buys Ballot's law to the problem ; but the temperature question is a more difficult one, for, unless the pressure

conditions have been steady for many hours, the winds are not actually moving from the localities which an inspection of the charts would lead one to expect them to be. In the course of a few hours, owing to movements of the cyclonic centres, the winds may box the compass, and when this is the case there is no considerable movement of air from one distant region to another.

The movement of cyclones, both great and small, depends upon the major features of the surrounding high- and low-pressure areas. Indeed, the movements of their centres obey Buys Ballot's law. Secondary cyclones within primary cyclones in the Northern Hemisphere move counter-clockwise round the centres of the primary cyclones ; but when they are near anticyclones they move clockwise round the anticyclones. Primary cyclones depend for their movements upon the position and size of anticyclones, but the daily charts do not in many cases cover sufficiently large areas for the paths of large cyclones to be predicted.

When we are dealing with the monthly mean pressures the conditions are more simple ; for it is then the average direction of the winds that is indicated by the isobars, and the localities from which the general winds move and where they move to can be seen.

An inspection of the daily pressure charts does not show that the general pressure changes which occur, often once, twice or even oftener each month, are due to the oscillation of the low- and high-pressure areas from one position of comparative stability to another. However, geographical conditions are important, for the lowest pressures generally occur over the oceans or near their margins. Mountain ranges and plateaux, like those of Asia, also make themselves felt. Apart from this, cyclones may appear almost anywhere, and then drift with the general circulation.

For the purpose of obtaining figures showing the daily changes of pressure which are taking place the better plan would seem to be to give the pressure changes which take place over some large region such as the Atlantic Area ; for in this region the changes of pressure with latitude indicate that the pressure over the whole area rises and falls in an irregular but periodic manner. However, the reasons for adopting this area will be considered later.

Judging by the pressure distribution and wind directions of the Southern Hemisphere, it appears that if it were not for the presence of the continents of Europe, Asia and North America, the two low-pressure areas of the Northern Hemisphere would merge, and the winds would circulate

around the North Pole much as they do around the Antarctic Continent, but with varying force. In this respect, therefore, the distribution of land and sea does influence the nature of the pressure distribution in both hemispheres greatly.

The very remarkable changes which have been shown to take place from day to day in the mean pressures of such large areas as the Arctic Area and the Atlantic Area which we have been considering are very noteworthy ; for if the pressure falls in one locality it must rise in some other in order that the mean pressure over the whole earth may remain the same. It is likely where seasonal changes are concerned that when the pressures are high in middle and high latitudes in the Northern Hemisphere they are low in similar latitudes in the Southern Hemisphere ; but it seems more likely that the transfer of air is of a more local character in the case of the more rapid monthly periodic variations. These points can only be quite satisfactorily settled when we have daily charts covering both hemispheres.

To cause such displacements of air as are required to produce these pressure variations, the mean temperature of the atmospheric air column over large areas must suffer great fluctuations at considerable heights, for the mean pressures at the earth's surface are not such as would be expected from the ground temperatures.

It will be realised that such great pressure changes as the charts show, especially if of a prolonged nature, lead to great changes in the general circulation of the atmosphere. For example, in England high Arctic pressures result in the weakening of the westerly winds, or even in their total suppression. We then experience a littoral or continental climate. However when the pressures are low in high latitudes, the general circulation is cyclonic, and the winds are south-westerly, bringing with them warm air, secondary cyclones and moisture.

According to the monthly weather report of the Meteorological Office for January, 1929, a month of high pressure over England, the weather was very cold, with a decided deficiency of precipitation. There was a conspicuous paucity of south-westerly winds, northerly and easterly winds occurring with considerable frequency.

As will be seen from Fig. 88 there was a period of low but variable pressure over the Atlantic Area during October, November and December, 1929, and weather in England was very unsettled and wet, winds from between west and north-west being unusually prevalent. Similarly January, 1930, was a period of low pressure over the Arctic regions,

and the weather in England was mild and wet, with violent gales, the prevailing winds being south to south-westerly and frequently strong.

For a few days during the first six months of 1930 it was found possible to ascertain the mean pressures of the whole area around the North Pole north of latitude 60° N., and these pressures can be compared with those of the smaller Arctic Area which omits the East Siberian quadrant, and also with the Atlantic Area. The figures are given in Table XVI. Here column A is for the Arctic Area, B for the whole area north of 60°, and C for the Atlantic Area. The means of all three areas are in close agreement ; but C differs from the others considerably in individual instances owing to the fact that it extends farther south.

TABLE XVI.

Mean Pressures during January—June, 1930.

Date.	A.	B.	C.	Date.	A.	B.	C.
Jan. 3	1013	1017	1006	April 1	1005	1009	1005
,, 10	1006	1008	1006	,, 24	1025	1025	1017
,, 15	1020	1022	1015	May 2	1009	1010	1015
Feb. 12	1005	1007	1006	,, 9	1021	1020	1015
,, 26	1017	1016	1015	June 12	1006	1007	1015
Mar. 6	1001	1006	1014				
,, 26	1022	1020	1017	Means	1012·5	1013·9	1012·2

(*A*) Arctic Area. (*B*) Area north of 60° lat. (*C*) Atlantic Area.

During January, 1929, when pressures were high over the Arctic Area, only eleven cyclones are charted as having existed in that part of Europe shown on Chart 2 of the monthly weather report. However, during October, when the pressure was low, thirty are noted as having been present. Indeed low barometers in high latitudes seem to be largely due to the formation there of numerous more or less deep cyclones, as well as to a general fall of pressure.

On 10th January, 1929, for example (Fig. 87), the notable range of pressure was due to high anticyclonic conditions rather than the presence of deep cyclones, as also was the case on 27th January. On 16th January, 1929, pressure was lower and the pressure range smaller.

On 5th December, 1929, the conditions were quite different, for a very deep cyclone, the centre of which lay

to the east of Ireland, dominated almost the whole of the Atlantic Area, with the result that pressure ranges were great and mean pressures low.

In January, 1929, pressure range curves and mean pressure curves rise and fall in unison, whereas in December, 1929, the reverse is the case. This is an important consideration and will receive further notice in the next chapter.

In some respects the facts seem to be opposed to the hypothesis that cyclones are caused by horizontal differences of temperature ; for the centres of low pressure at the earth's surface do not cover the areas of high surface temperature. It has been contended that it is the flow of warm air to high latitudes along the earth's surface and its ultimate rise over cold air in its front that furnishes high-latitude cyclones with their energy. However it is difficult to see how such a movement could commence, for air should rise where the heated air lay, and draw in cold air on all sides. We really have to explain why cyclones are largest and most powerful in high latitudes in winter, and least powerful during the summer months when the ground temperature is about 70° F. above that of the winter months. Under such temperature conditions, if it is the surface temperatures that are the motive power, cyclones should be more prevalent during the summer rather than during the winter.

We thus have to recognise two types of pressure differences in high latitudes, the one due to a general lowering or raising of pressures, and the other to the development of great local differences of pressure. As a rule low pressures and cyclones are closely associated even when large areas are considered, but this is not always the case.

The actual height of the barometer over a large area of the Arctic regions, although a feature of great importance, is not the most noticeable pressure phenomenon of the area. We can easily see from the pressure charts that the intensity of the cyclones and anticyclones varies greatly from time to time, but the variations in the actual pressure differences must be shown by calculated figures to be properly appreciated.

To show the amount of disturbance due to varying pressures and give figures to indicate its magnitude, the following method has been adopted.

It has already been pointed out that the daily weather charts are often incomplete as regards distant localities. However, they are seldom so over the Atlantic Area, which covers a large area extending from the Caspian Sea to Hudson's Bay, and from lat. 40° N. to the north coast

of Greenland. It is, therefore, a region which represents the conditions over a large land as well as over a large water area.

The daily pressures for 27 points over the Atlantic Area have been tabulated for four years, and for each day the mean of the five highest and five lowest pressure readings taken. The difference between these two means has been regarded as the "pressure range" for the day. Of course the values can only be regarded as relative activity numbers ; but they do give a good idea of the disturbed condition of the area resulting from the presence of cyclones and anti-cyclones.

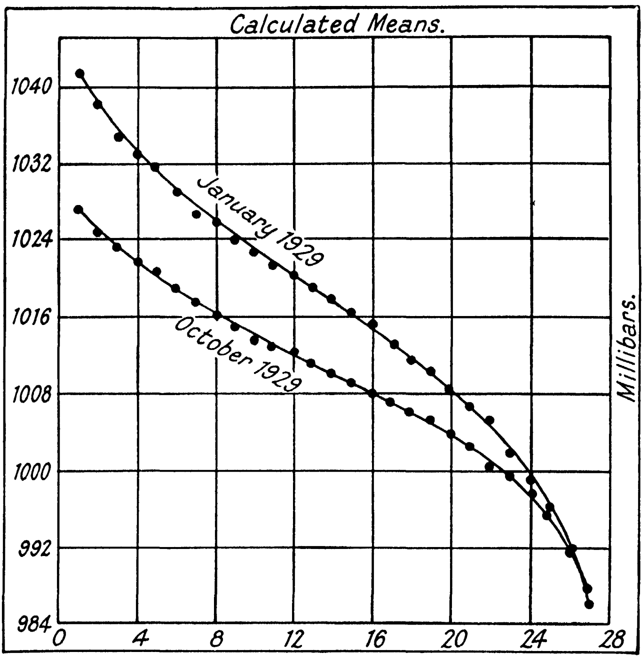


Fig. 126.—Characteristic Pressure Curves for January and October, 1929.

When the pressure is very uniform over a large area, however low or high the mean pressure may be, deep cyclones and marked anticyclones must be absent ; but however high or low the mean pressure, if the pressure is very irregularly distributed, there must be cyclones and anticyclones of some magnitude. It thus follows that a large pressure range is accompanied by strong winds and unsettled weather, whereas a small pressure range is accompanied by more settled conditions.

If the pressures at all the 27 points are ascertained and plotted in the order of their magnitude, a line drawn through

them is regarded as the characteristic pressure curve. Similar mean curves may be drawn for any required number of days.

Two main features present themselves, one that there is a considerable variation in the pressure ranges from day to day, and the other that a markedly greater pressure range obtains during the winter than during the summer.

As a rule when the pressure range is great the mean pressure is low ; but, as has already been stated, this is not always the case. The Atlantic Area, for which the figures have been calculated, is only a small portion of the area north of latitude 40°. Across this latitude there would appear to be a transfer of air backwards and forwards as the mean pressures vary. Before this point can be settled, however, we must have daily isobaric charts for all longitudes of the Northern Hemisphere.

On Fig. 126 the mean pressure characteristic curves for January and October, 1929, are shown. We have seen that January was a high-pressure winter month and that October was a low-pressure winter month. The curves show that the high mean pressures of January were due to high pressures becoming more pronounced, whereas the low pressures were little changed. Similar curves for May and July, 1930, two summer months, showed that the higher pressures of May were due to an increase of pressure which affected cyclones and anticyclones equally, thus leaving the mean monthly pressure ranges about the same.

The estimation of the pressure range really furnishes us with a good means of giving the characteristic curve a numerical value which serves as a weather activity figure.

The most striking features of the pressure ranges are, as will be seen from Fig. 125, that they are about twice as great during the winter months as they are during the summer months, and that their oscillations of magnitude are also greatest during the winter. It is often stated that the cyclonic activities of which they are the result are due to the conflict of the extreme cold air of the Arctic winter with the air from surrounding warmer regions. However it can be shown that such cannot be the explanation. It is a tacit assumption of such an hypothesis that, if the temperature is low on the surface of the earth, the atmospheric pressure must be high, and that when the surface temperature is high the pressure must be low. But near the poles during the winter the pressure is not high ; it is lower than during the summer. The surface temperature is colder during the winter than during the summer in the Arctic regions, but the cold air

consists only of a thin layer on the earth's surface and does not greatly affect cyclonic activity.

The great pressure ranges and low mean pressures within the Arctic Circle are phenomena well worth the careful consideration of meteorologists. Indeed the pressure distribution which is shown by the isobars, and the consequent wind directions, are not such as would be expected from the surface temperature isotherms drawn on our charts. In middle and high latitudes the winds blow as the isobars prescribe, but seldom in accordance with the dictates of the isotherms.

CHAPTER XII.

SUNSPOTS AND SOURCES OF CYCLONIC ENERGY.

METEOROLOGISTS are agreed that many climatic and seasonal phenomena are not such as we should expect to experience as a result of the operation of known physical phenomena. Such being the case we must consider to what extent the sun may influence the earth's atmosphere other than by its heat and light rays. For example the rôle possibly played by material particles ejected from the sun has been much discussed ; but many are still of opinion that although some terrestrial magnetic and optical phenomena may be due to them, they can safely be disregarded when climatic phenomena are in question. Grave doubts as to whether the earth's atmosphere can be affected to any considerable extent by such radiations are expressed by many scientific writers ; especially is this the case when sunspot phenomena are the subject of discussion. However, there are others, who although not satisfied on many points, are yet impressed by certain coincidences between the position of sunspots on the sun's disc and the occurrence of magnetic storms, etc. on the earth.

If it were possible to explain satisfactorily all important meteorological phenomena merely by appealing to the sun's light and heat rays, disregard of other radiations would be justifiable. However, insolation, as ordinarily understood, seems to be quite unable to help us to account for such important matters as the general circulation of the atmosphere, irregularities of weather and climate, especially of a secular (long-period) nature, and the formation of cyclones. We must look for an explanation, therefore, to some other insolation phenomenon. Not enough is known about the sun's activities to say that it does not emit material particles which could affect the earth's atmosphere markedly. Indeed the sun is the seat of tremendous activity, and as there is clear evidence that it does influence auroral and magnetic phenomena on the earth, no apology is needed for considering such solar phenomena here.

Of recent years much fresh information has been obtained concerning weather conditions in high latitudes, and the additional facts so brought to light seem to favour the view

that sunspots, especially when near the centre of the sun's disc, do greatly affect atmospheric pressures in high latitudes. Such being the case an attempt will be made to explain in a simple manner how the matter now stands. It involves terrestrial magnetism, auroral lights, and mean barometric pressures in high latitudes.

When seen through a telescope the sun seldom appears as a clear bright orb. As a rule one or more dark spots or groups of spots appear upon its surface. Fig. 127 shows a number of spots which were crossing the sun on 21st March, 1920. Each large spot consists of a dark centre surrounded by a less dark area. These are known as the "umbra" and "penumbra," respectively; but they certainly are not shadows. The dark centre is really bright and hot, but appears to be dark when contrasted with the much hotter and brighter surrounding surface of the sun. The sun's general surface has a temperature of about 6,000° C., and the temperature of the umbra is probably about 4,000° C.

Very little is known with certainty concerning the nature of sunspots. On this account it is somewhat hazardous to argue that they are capable of affecting any strictly terrestrial phenomena. However this may be, it is as well to form some concrete conception concerning their structure and activities as a means of forming a mental picture of the facts, even though the theory may be defective in some respects. Indeed there are few theories that do explain correctly all the facts of any science; but in all cases theories do help the mind to grasp the facts without great difficulty.

Sunspots apparently are masses of matter several thousands of degrees cooler than the surrounding gas, and floating at such levels that they are visible. On this account they appear black by comparison with the sun's general surface. But if they are colder than the surrounding fluid, why do they float and where do they come from? They are relatively short-lived, some of them appearing and disappearing in the course of a few days, whilst others survive during several revolutions of the sun. They are far too large to have come to the sun from space, and have probably come from great depths owing to the formation in them of "bubbles" of lighter fluid matter, and as they rose the gas has expanded and cooled adiabatically, just as does rising air in the earth's atmosphere.

The liberation of light gas is probably due to the disruption of the atoms of certain elements. This process, we know, is going on in the solid earth, and by measuring

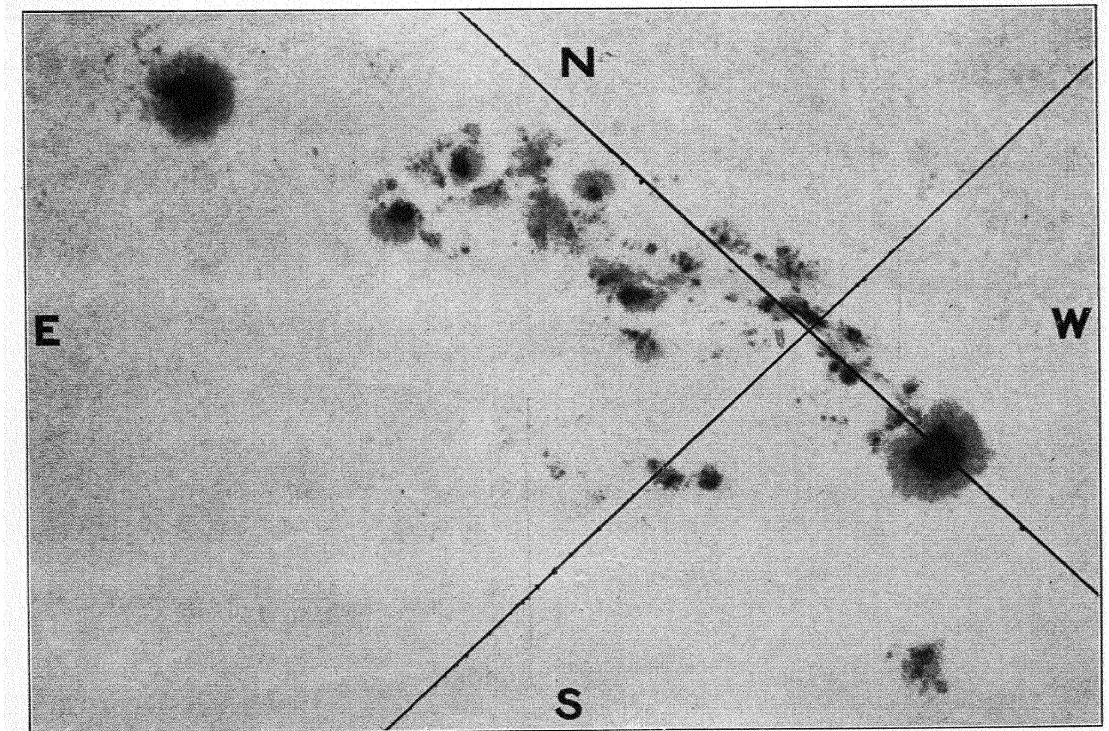


Fig. 127.—Stream of Sunspots, March 21, 1920.

[*Photographed at Royal Observatory, Greenwich, and reproduced by courtesy of The Astronomer Royal.*]

the quantities of certain lighter elements produced we have been able to ascertain the ages of the various rock formations of which the crust consists. In the course of such " radio-active " changes many gases of a temporary nature, known as " emanations," are formed, as well as elements such as helium. On nearing the sun's surface the light gases contained by the rising masses escape, and rush out into space at great velocities, largely at right angles to the sun's surface.

Omitting all consideration of sunspots for the moment, the great mass or shell, if not the whole of the sun, called the *photosphere*, is regarded as being gaseous. (The liquid and gaseous forms of matter are both considered to be in the " fluid " condition). It is admitted that the hypothesis here adopted, that matter rising from great depths in the sun cools adiabatically to temperatures much below that of the surface, conflicts with Faye's theory that the sun's stores of energy are rendered available at the surface by means of vertical convection currents, that is to say by the bodily transport to the surface of intensely hot matter. Instead, it is suggested that the transference of large masses of such material to the surface of the sun results in the formation of cool sunspots, the upward movement being the result of radioactive changes leading to density changes. The typical spot consists of a dark centre or *umbra*, surrounded by a *penumbra* in the form of a more or less complete ring which is darker than the surrounding solar surface but not so dark as the umbra. However, the umbra is not dark because it is the bottom of a deep cavity, nor is the penumbra brighter than the umbra because it is in a shadow. The variations of brightness are due really to low temperatures in the case of the umbra, and it may be that the penumbra is largely due to the gaseous photosphere overlapping the dark umbra. Many spots do actually appear to be photospheric excavations, but calculation shows that if they are, the depth of each spot varies greatly.

Herschel and Wilson long ago suggested that a certain " empyreal " gas was generated in the body of the sun, and formed openings in the sun's luminous surface, which shewed the darker material of the sun's mass below. It has been said with respect even to this untenable theory that a definite hypothesis, even if a false one, gives holding-ground to thought, and that truth emerges sooner from error than from confusion.

That sunspots are not portions of a dark solid surface of which we obtain glimpses through holes in an incandescent

photosphere, is rendered probable by their differential movements ; for they have not all the same angular velocity. Carrington, by a careful study, ascertained that the spots had no single period of revolution, their angular velocity being greater near the sun's equator than near the poles. It thus appears that sunspots, or even groups of sunspots, are distinct entities, floating with the currents in the gaseous photosphere.

Fig. 127 shows the great stream of sunspots of 21st March, 1920, the length of which was 200,000 miles, the total area of spots being about 3,000 millions of square miles. The cross-lines are the images of the spider-threads used in the measurement of the position of each spot.

Upon the photosphere rests the *chromosphere*, and above it the *corona*. The latter is a very brilliant and beautiful object only fully seen when the sun is totally eclipsed. It appears to be formed of tenuous matter high above the sun's surface rendered visible mainly by the sun's reflected light.

There is no abrupt change between the photosphere and the chromosphere, their differences being such as might result from variations in pressure and temperature. The same can be said of the corona.

The most interesting features of the chromosphere and the corona are the solar prominences. These, it has been found possible to study by spectroscopic methods even when the sun is not eclipsed. They vary enormously in size and behaviour. One main group includes small prominences which appear in the form of rockets, bright jets and arches and metallic protuberances. These can usually be definitely connected with sunspots, especially young and active ones, but rarely with old ones.

The suggestion that the sun and its attendant planets, moons, comets, etc., are built up of the same elemental forms of matter, and that these bodies differ only in physical condition, temperature and density, may seem to be a conception incapable of proof. Indeed any theory based upon such an idea should first of all show how the unity of constitution of the solar system has been proved.

There are few who have not become familiar with wireless broadcasting and reception apparatus, and we all commonly speak of wireless waves of various lengths, and of receiving apparatus capable of tuning in to these various waves. They are matters of common knowledge ; and we know that signals can be sent out by a station in England and picked up in Australia and other distant countries, and the messages deciphered there. Not only so, but the

actual voice can be converted into wireless waves, transmitted as such to any part of the earth and reconverted into audible speech again.

These wireless waves are similar to light and heat waves in almost every particular. Now light from any source consists of broadcast waves which tell us what is taking place at the point of origin, just as ordinary wireless waves tell us what is going on at the broadcasting station. The only difference between broadcast wireless waves, light waves and heat waves, is length. The length of a wireless wave is measured in metres, those of heat and light in small fractions of a centimetre.

A wireless receiver can be tuned in to pick up many different wavelengths, but such is not the case with an atom ; for an atom is really both a broadcasting station and a receiving station operating upon a definite number of wavelengths. To bring the atom into operation in this manner, it is necessary only to raise its temperature sufficiently high to make it hot or incandescent. If the element be solid, or if it be a highly compressed gas, the atoms " jar " each other and it then sends out waves of nearly all lengths. This jumble of different waves can be separated out and its components placed in order of wavelength by passing the light through a prism of glass, rock salt, etc. When spread out in this way, the waves from an incandescent solid or liquid, or a greatly compressed and heated gas, give a continuous band of light showing all the colours of the spectrum. A similar band of light is produced by allowing the rays of the sun to pass through a short, very narrow slit, in front of which is placed a prism of glass or other transparent substance. The light is then spread out as a band of the same depth as the slit and showing all the colours of the rainbow. However, when the source of light is that of the sun, the band of variously coloured light is seen to be crossed by numerous dark bands, indicating that certain wavelengths are missing.

Experiment has shown that an element in the incandescent gaseous state can broadcast only on a certain definite number of wavelengths and that a cool gaseous element can receive or *intercept* only particular wavelengths. Indeed, it has been found that all elements, when sufficiently tenuous and heated to incandescence, radiate distinctive spectral lines, by which they can be distinguished. For example, sodium vapour gives two luminous yellow lines very close together. In the spectrum of the sun there are two similar lines of nearly the same wavelengths, but they are black, not luminous. This requires some explanation. In the case of

a dense, greatly heated gas, or a liquid or solid, the spectrum is a continuous band of the colours shown in the rainbow. In the case of the sun there is a low-pressure gaseous envelope, sufficiently cool not to send out broadcast waves, and this envelope intercepts the waves which each element it contains could broadcast if sufficiently hot.

Now in the case of the sun we have the highly compressed and heated gases of the photosphere giving off a continuous coloured spectrum. Above or in front of this the gases become cooler and cooler, and begin to absorb waves of certain lengths, in accordance with their elemental composition. The result of this absorption is to cut off waves of the same kind emitted by the photosphere, and the nature of the cool gases is shown by dark lines in the sun's spectrum. Some elements, such as iron, have hundreds of distinctive lines, others comparatively few.

A study of its spectral lines tells us that the sun contains the same elements as the earth, and that there is every reason to believe that the solar system is composed of the same kind of matter throughout, but existing in different physical states according to local conditions of pressure and temperature. Meteors also have the same story to tell.

The spectroscope really puts us into a kind of wireless communication with the sun and other heavenly bodies, and tells us much of what is going on in distant space. Indeed, it not only tells us what matter in space is composed of, but it also gives us information concerning the movements to which such matter is subject.

The aurora has been mentioned several times in this book, but hitherto has not been described. In its least impressive form it is merely a sky more brightly illuminated than usual, nearly always occurring in high latitudes in the northern or southern sky. It most frequently takes the form of an arch of light above a dark segment of the sky. The lower edge of the arch is well defined, but from the upper edge bright rays of light shoot upwards (see Frontispiece). In the Arctic and Antarctic regions magnificent displays are to be seen, in which the rays appear like numerous curtain folds, the brighter and more continuous folds at the bottom appearing like frilled draperies. One of the most beautiful forms it takes is the Corona. It then has a dark centre surrounded by a crown of light which breaks up into radial rays.

Astronomers have found that when there is a magnetic storm on the earth a spot may also be expected to be present near the centre of the sun ; but magnetic storms do not

always occur when the sun has a spot or spots near its centre. This applies to auroral displays as well as terrestrial magnetic storms, and we shall find the same fact illustrated when weather changes come to be considered. Thus it appears that not all spots are active, or that their radiations sometimes pass into space without encountering the earth. It appears that sunspots affect the earth rather by the emission at very great velocities of beams of electrified matter, rather than by any form of wave radiation. On reaching terrestrial regions such matter is directed by the earth's magnetic field towards the poles, and this is regarded as the reason why the aurora is almost wholly confined to high latitudes.

The question as to whether sunspots affect weather has been much discussed. As a rule the problem set for solution has been to ascertain if any of the climatic factors which admit of accurate measurement vary in sympathy with sunspot cycles. The facts of Meteorology, however, are much too complex for general treatment on such lines. That there is evidence that weather changes do occur in sympathy with sunspot cycles was contended by Dr. Meldrum of Mauritius, who found that increased rainfall and atmospheric agitation attended sunspot maxima. There certainly does appear to be a fairly close relationship between sunspot numbers and the rainfall in certain parts of Equatorial Africa, especially on the plateau on which Lake Victoria stands. This relationship is brought out in Fig. 128 in the form it was given by Sir Richard Gregory in his 1930 address to the Meteorological Society.

The rainfall area of Central Africa is very interesting, for nearly the whole of the wet belt moves backwards and forwards across the equator with the march of the seasons. In January, with a rainfall reaching in some places 12 inches, the wet area lies almost wholly to the south of the equator, and extends as far south as the northern portions of Cape Colony, whilst in July the area of greatest rainfall is between the equator and 20° north latitude. This striking movement of the wet area would appear to be due partly to the Monsoon conditions of Asia.

In previous chapters it has been stated that the atmospheric pressure over the North Polar Area varies very irregularly indeed from day to day and month to month, and there is no reason to believe that pressure conditions in the Southern Hemisphere do not suffer similar changes. These pressure changes are found to be quite irregular when short periods of time are considered. They cannot be attributed to changes in the solar constant. Indeed the

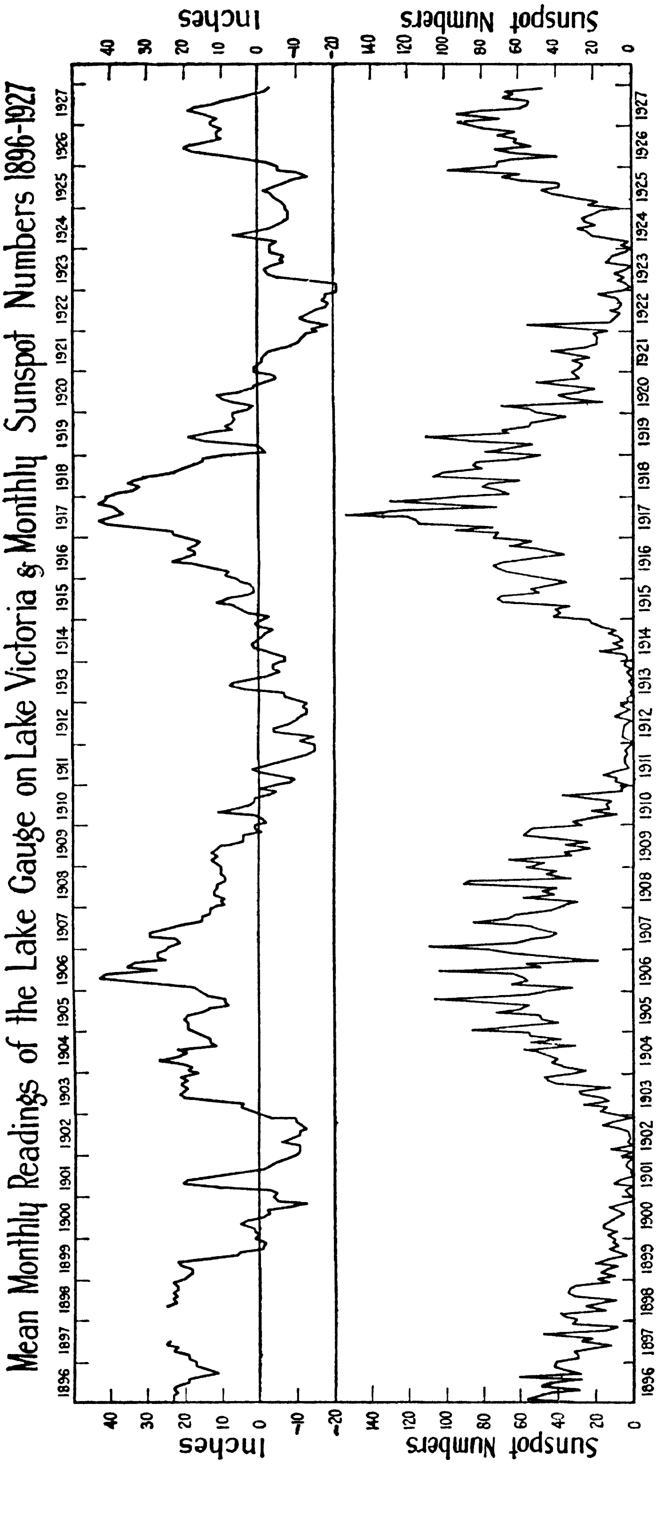


Fig. 128.—Periodic Changes of Water Level in Lake Victoria, Africa.

(*From the Quarterly Journal of The Royal Meteorological Society, by permission.*)

average pressures for the winter months in high latitudes are generally less than those for the summer months.

Attention has already been called to the fact that in spite of the frigid conditions obtaining in both the Arctic and Antarctic Areas, the average polar atmospheric pressures are less than those over the horse latitudes. This is especially the case in the Southern Hemisphere, where the great Antarctic Cyclone dominates the whole area south of the horse latitudes. Even in the Antarctic Area there are good reasons for believing that the pressures show considerable changes from time to time, the heating of the atmosphere being irregular.

No satisfactory explanation has yet been given to show why, in the polar regions, the pressures generally are less than they are in the tropics ; or why the pressures occasionally are very high there. Although this matter has already received a good deal of attention, it will be well to reconsider it in some of its aspects.

As the phenomena of the circulation of locally heated water are the same in all essential respects as those of similarly heated air, we will again consider the case of a trough three feet long and one foot wide, with one foot of water in it. (If length and depth were in proportion to the distance of the pole from the equator and the thickness of the layer of air involved, the length of the trough would have to be about nine hundred feet.)

If one end of such a trough be heated, the water there expands, becomes slightly less dense, and forms a prominence. In a mobile substance such as water, however small this decrease of density may be, the conditions set up are not stable, and the water of the prominence flows off along the upper surface in an attempt to level matters. As soon as this movement commences, cold water flows in below, is warmed there, and rises in its turn. In this way a circulation is set up as shown by the arrows in Fig. 41. Now such conditions of circulation cannot be wholly reversed unless the other end of the trough be warmed instead.

In Fig. 42 the conditions of flow are given when both ends of the trough are heated and the centre cooled, and the circulation thus produced is the usual one in the earth's troposphere. The two lower currents move towards the ends of the trough in opposite directions, just as do the trade winds and the prevailing westerlies. The conditions also resemble those of the earth as regards pressure, for the two end columns of water are warmer and lighter than the water of the cooler central column. On the earth the warming in

the neighbourhood of the equator is regarded with good reason as resulting from the light and heat rays received from the sun, and should vary in sympathy with variations in the solar constant. But what is the influence that warms the air in high latitudes over the poles, and warms it so much that, in spite of the frigid conditions near the earth's surface, the whole mass is at most times kept so warm that low pressures and therefore cyclonic conditions prevail there?

Many meteorologists have expressed themselves as being in doubt as to whether the low pressure in the centre of a cyclonic depression is due to the winds circulating around the centre, or whether it is the movement of the circulating winds that causes the fall of pressure. Few doubt, however, but that there is a balance maintained between the velocity of the wind and the pressure gradient, and that, as the velocity of the wind decreases owing to friction, the pressure in the depression increases.

It is not at all clear how the velocity of the wind could vary except in sympathy with variations of pressure. However, a rise of temperature of the air in the centre of a cyclone, no matter how high it occurred above the earth's surface, would cause a fall of pressure at the earth's surface, and increased cyclonic activity, and we have no reason to believe that changes of pressure can result from anything but changes of density due to changes of temperature.

According to current theory, the warming of the earth results entirely from the heat and light radiations received from the sun, the seasonal changes being caused by the varying elevation of the sun, and the changing length of the day. For an explanation of the ever-changing weather conditions that occur from day to day and month to month an appeal is made to the variations that are considered as constantly taking place in the value of the solar constant, and also to effects produced by the irregular distribution of land, mountain, sea and ocean. This latter factor, however, should rather be considered responsible for the differences of climate which are often found to exist between localities having similar latitudes. From the point of view of theory the assistance a consideration of the variation of the solar constant gives us is not at present of much value; for the magnitude and variations of this constant are very difficult to measure. Much excellent work in this direction has been accomplished at the Astrophysical Observatory of the Smithsonian Institution at Montezuma, Chile.

It is thus by no means agreed that the fluctuations in the sun's heat stated to occur are the real ones; for consider-

able and varying corrections have to be made in the observed results for atmospheric absorption. However, C. G. Abbot considers that, owing to improved methods of observation and calculation, good results have been obtained since 1919.

Although there must remain in the minds of those who have studied the figures some doubt as to whether they represent the facts correctly, it is advisable to consider the nature of the problem.

Table XVII gives the Smithsonian solar constant figures for March, 1930, and other months show about the same range of variation. C. G. Abbot considers that, looking at the whole of the results obtained since 1918, there is a marked five-day period of change.

TABLE XVII.

Solar Constant Values.

Montezuma.

March, 1930.

1	1·941	11	..	21	..
2	1·945	12	1·931	22	1·934
3	1·940	13	1·940	23	1·936
4	1·940	14	1·935	24	1·951
5	1·939	15	1·937	25	1·958
6	1·937	16	1·940	26	1·947
7	..	17	1·943	27	1·939
8	..	18	1·938	28	1·939
9	1·941	19	1·938	29	1·935
10	1·936	20	1·931	30	1·935
				31	1·940
Means	1·940		1·937		1·941

Since 1928 the International Astronomical Union has issued a Bulletin giving among other things character figures for solar phenomena. In it the activity of sunspots for each day is expressed in Wolf figures. Such figures are given for the whole disc and for a central area. The choice of the size of this central area is an arbitrary one. W. Brunner strongly favours the adoption of such a central zone and remarks that if anything of any use can be obtained in this way, it will certainly be by considering some such small area ; for it will certainly be the distance from the centre of the disc that will prove the decisive factor.

The presence on the sun's surface of a few cool spots

could not produce any marked effect upon the solar constant; for even when they are unusually active their combined areas are only about $\frac{1}{700}$ of the sun's visible hemisphere. However, the possibility must be considered of the magnitude of sunspot areas and solar constant values being the result of some common cause, and if such were the case they would probably vary in sympathy.

It would appear that the disturbed areas on the sun from which matter is ejected into space, and over which sunspots are generally distributed, remain somewhat active even when sunspots are rare. Indeed sunspot activity appears to be the cause mainly of secondary cyclones, the more general emission of a secular periodic character being responsible for the more widespread pressure conditions on the earth. Secondary cyclones appear and disappear quickly and are responsible for much of the precipitation which occurs over areas of low relief.

At Greenwich Observatory photographs of the sun are taken each day when the sky is not overcast—on overcast days photographs taken at other observatories are used to complete the daily series. The size of each spot or group of spots is measured, and its position and distance from the sun's centre are noted. The results obtained are published annually under the title "*Greenwich Photo-Heliographic Results.*" In this publication a number is given to each spot or group of spots. Notes are given describing the nature of the spot or group of spots, and also other relevant information.

As a result of the co-operation of a number of astronomical observatories, a figure is calculated for each day which is called the "Wolf relative sunspot number" and gives with some accuracy the intensity of sunspot activity from day to day. Two figures for each day are furnished. One for the whole disc and the other for sunspots within 30° on each side of the central meridian. It is the latter which will be considered here.

The "Wolf relative sunspot number" is calculated by a purely empirical but simple method, and as we shall see it does appear to be a useful figure. The "*Bulletin for Character Figures of Solar Phenomena*" is published by the Eidgen. Sterwarte in Zurich.

In addition to the presence of dark spots, the sun's disc is seen, under suitable magnification, to have a mottled or granulated appearance, the granulations appearing to be in rapid motion with velocities of 5 to 20 miles per second and to be continually changing their form.

Owing to the very high temperature of the sun it is

concluded that the matter of which it is composed must be in the gaseous rather than either the liquid or solid condition. At the sun's surface the force of gravity is about 27 times greater than it is at the earth's surface, but owing to its gaseous condition and high temperature, the sun's density as a whole is only about one quarter that of the earth. It is somewhat difficult under these conditions to realise what the *photosphere*, which the sun's surface is called, is like ; for there is a mobile, gaseous, partially transparent atmosphere, called the *chromosphere*, above it.

It is scarcely likely that there is an abrupt change in the physical condition of the sun between the photosphere and chromosphere above. Rather is it likely that what we call the " surface " of the sun is the level at which the gas ceases to be incandescent and becomes transparent.

Upon the photosphere, as we have stated, rests the more transparent chromosphere. The surface of the photosphere is incandescent, whereas the chromosphere is sufficiently cool and tenuous to be partially transparent, but nevertheless able to absorb many of the light and heat waves passing into it. This layer has a thickness of 6,000 to 14,000 kilometres, and it is in its lower portion, for a thickness of 600 to 1,000 kilometres, that the absorption of certain light waves largely takes place. It is often called the " reversing layer." When the light from the sun, which has passed through the chromosphere, is passed through the slit of a spectroscope and the band of light thrown upon a screen, vast numbers of dark absorption lines are seen on the band produced, and it is these lines which tell us of what elements the gases of the chromosphere are formed.

Outside the chromosphere we have the *corona*, which at the moment of total eclipse by the moon, flashes out as a bright aureole surrounding the eclipsed chromosphere and photosphere. It is pearly white and a little brighter than the full moon, has a very complex structure, and its shape varies with the sunspot cycle in a very marked way. Much of the coronal light has been shown to be sunlight reflected by small particles of matter thrown to distances of two or three solar diameters from the sun.

The most remarkable phenomenon of the corona is the existence of prominences or enormous tongues of " flame " standing out from the sun's limb and often reaching to very great heights. H. W. Newton has measured the vertical velocities of matter thus thrown out by the sun, and states that velocities of 20 to 40 kilometres per second are frequently met with, high velocities being most common near sunspots.

Prominences vary enormously in shape, size and behaviour. One main group includes small prominences in the form of rockets, bright jets and arches—they can be definitely connected with a spot. Young spots are most frequently found associated with prominences, but old spots rarely so.

Although some prominences occur in the neighbourhood of spots, those in high-latitude belts do not show any such connection ; it is also found that the majority of those in low latitudes are not connected with spots, neither are those of the group which includes the large massive forms.

A particle of matter ejected from the sun at a velocity of about 450 miles per second would pass into space far beyond the earth's orbit. The prominences and clouds of the corona do show that large quantities of matter are thrown out to great distances, for clouds of matter have been observed moving away from the sun at velocities of 390 miles per second.

Prof. Chapman calculates that the pressure of sunlight on certain very small particles at some distance from the sun would accelerate them, and throw them into space, the velocity of their movement over the greater part of their journey from the sun to the earth remaining nearly uniform. The time taken to reach the earth would be a little over one day.

So closely are the variations in the activity of the sun associated with variations in the number of spots on its surface that it has become customary to speak of sunspot periods or cycles rather than sun activity periods. Indeed, at present, it does not seem possible to deal with the sun's activity in any other way ; but it must be clearly understood that matter thrown into space by the sun, probably from prominences, need not all come from sunspots.

For many years it was considered that no trace of regularity could or would be detected in the appearances and effacements of sunspots. Fortunately Heinrich Schwabe of Dessan in 1826 commenced to observe the sun whenever possible, and kept daily records of how many spots were visible on its disc. In 1851 a table of sunspot statistics collected by him was published, and it was at once recognised that the spots did vary periodically both in size and number.

Sunspot records may give either the number of spots, their total area each day, or Wolf activity figures, and although when short intervals are considered the figures show great fluctuations, yearly averages show well-defined oscillations. The following table, after Chree, shows the sunspot values for 66 years.

TABLE XVIII.

Sunspot Values.

1856	4·3	1878	3·4	1900	9·5
1857	22·8	1879	6·0	1901	2·7
1858	54·8	1880	32·3	1902	5·0
1859	93·8	1881	54·3	1903	24·4
1860	95·7	1882	59·7	1904	42·0
1861	77·2	1883	63·7	1905	63·5
1862	59·1	1884	63·5	1906	53·8
1863	44·0	1885	52·2	1907	62·0
1864	47·0	1886	25·4	1908	48·5
1865	30·5	1887	13·1	1909	43·9
1866	16·3	1888	6·5	1910	18·6
1867	7·3	1889	6·3	1911	5·7
1868	27·3	1890	7·1	1912	3·6
1869	73·9	1891	36·5	1913	1·4
1870	139·1	1892	73·0	1914	9·6
1871	111·2	1893	84·9	1915	47·4
1872	101·7	1894	78·0	1916	55·4
1873	66·3	1895	64·0	1917	103·9
1874	44·7	1896	41·8	1918	80·6
1875	17·1	1897	26·2	1919	63·6
1876	11·3	1898	26·7	1920	38·7
1877	12·3	1899	12·1	1921	24·7

It will be seen that periods when the number of sunspots was numerous were followed by periods when they were scarce. Such recurrences have been found to mark the sunspot records which have been kept since 1826. The mean period of a cycle is about 11 years ; but it is an irregular one, for it may be as short as 8 years or as long as 17 years. The maxima may be sharp and strongly marked or relatively flat and weak.

When the mode of occurrence of sunspots is studied some very interesting features come to light. At the commencement of each phase spots first appear in latitudes 30° or 40° north and south of the sun's equator. They then appear successively in an irregular manner in lower and lower latitudes. Fig. 129 shows four such sunspot periods, the areas covered by spots somewhat resembling the outstretched wings of butterflies moving in tandem. Around the sun's equator it will be noticed that spots are few in number, and that there is a comparatively clear area separating one group from the other.

The problem has been to ascertain whether any physical phenomena on the earth vary from time to time in such a

way as to keep step with sunspot periods, *i.e.* are any changes going on on the sun's surface which are varying in unison with climatic or other changes on the earth?

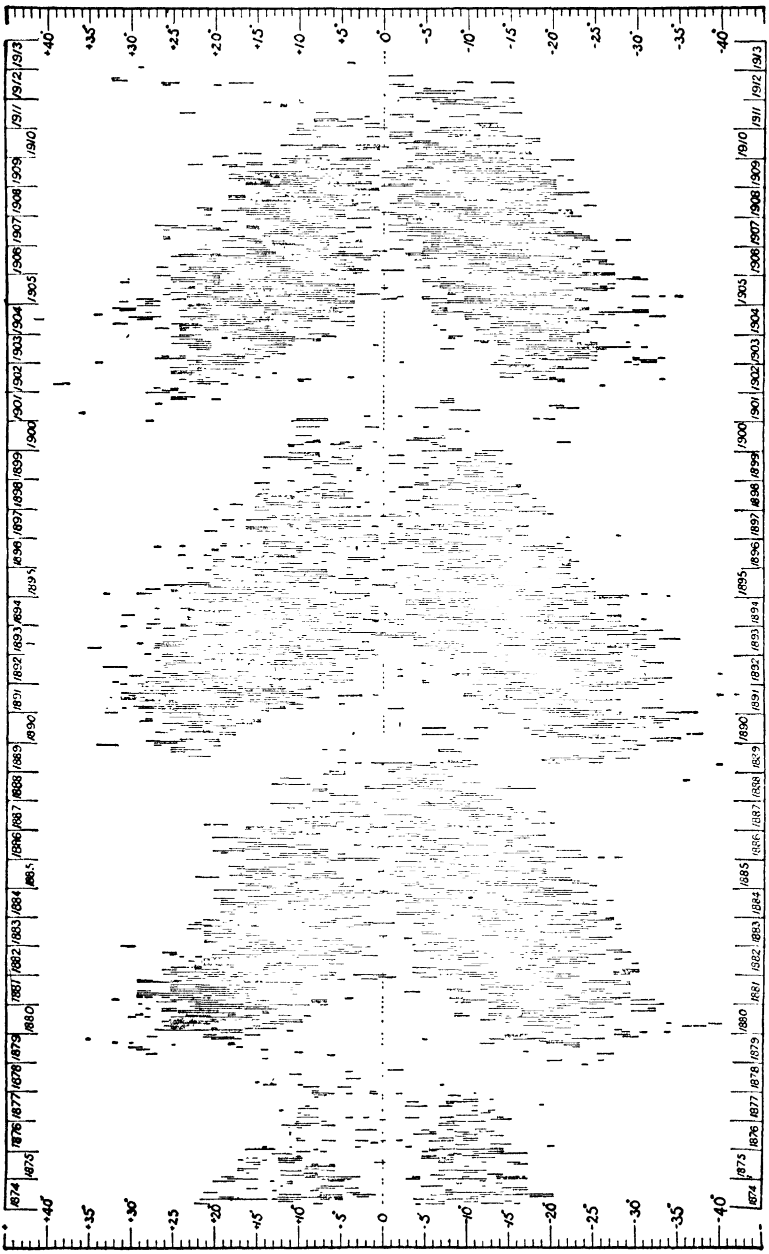


Fig. 129.—Distribution of Sunspots in Latitude throughout the Sunspot Circle.

(From Spencer Jones' "General Astronomy" by permission of Messrs. Edward Arnold & Co.)

When two such phenomena as the rising and setting of the sun and the alternation of light and darkness keep

regularly in step with each other, the correlation between them is said to be perfect or good. However Chree has shown that such is not the case when rainfall variations for Kew are compared with sunspot values, but that the correlation is good when movements of the compass are considered.

It will be necessary to use the word "correlation" somewhat freely, and when it is stated that the "correlation" between certain phenomena is good, it is meant that they change regularly in strength or magnitude the one with the other as time goes by. When the "correlation" is bad there is no such periodic agreement. Again, what may appear a rather good correlation during a short lapse of time may prove to be quite otherwise if comparisons are made over many months or years. Thus the moon appears to revolve round the earth in about the same interval of time that the sun appears to us to revolve on its axis ; but these phenomena only appear to be in step when the time interval considered is short. The correlation is really a bad one.

There is another kind of correlation that may be instanced. A marker at a rifle range target notices that a sharp sound is always heard a few moments before each "hit." However, many similar noises are heard without "hits" being registered. But this does not disprove the soundness of the theory that the noises heard immediately before each "hit" and the "hits" themselves are closely connected phenomena. Although this is the case, it is very desirable to ascertain why "hits" were not registered after each sound.

That there are periodic phenomena on the earth which vary in unison with the sunspot period is shown by the movements of the magnetic needle. To render this clear we must consider some of its movements which are not usually noticed. In the case of the ordinary compass the needle rotates and swings on a point placed some little distance above its centre of gravity. On this account it can revolve or oscillate horizontally very freely ; but a considerable force is required to disturb its horizontal disposition. However magnetic needles are made which are supported in such a way that they can move freely into any position the surrounding magnetic field may demand. Such "dipping needles" have been carefully balanced before being magnetised. In the Northern Hemisphere such a needle places itself so that it points downwards and northwards. At the North Magnetic Pole it points directly

downwards—*i.e.* stands in a vertical position. The position on the earth's surface of the North Magnetic Pole is shown by the large cross on Fig. 95, one of the pressure charts which have been described.

However, the magnetic needle does not stand motionless. The magnetic field which causes it to assume its position often undergoes remarkable changes. The lines of magnetic force (Fig. 56) frequently change their direction and density, and the needle moves. Sometimes it swings slowly from side to side and approaches to the true mean some four hours before noon, departing farthest from it between one and two hours after noon. The *range* of this daily variation has been found to increase and diminish in sympathy with the sunspot period, and the correlation is a good one.

There are also at times curious spasmodic variations called "magnetic storms." Roughly every ten years the disturbances reach a maximum of violence and frequency. Such storms in their incidence coincide with the sunspot period. That storms of this kind are in some way associated with particular spots is clear, for they occasionally recur after intervals of about 27·3 days, and this is the period of the sun's synodic revolution on its axis. In the case of 19 great magnetic storms between the years 1875 and 1903, Maunder pointed out that in every case there was a large spot near the central meridian of the sun. It must be stated, however, that the presence of a large spot on the sun is not necessarily an indication that a magnetic storm will ensue, for some spots are inactive, especially old ones.

The nature of the correlation curve between sunspots and the compass needle is shown in Fig. 130.

A magnetic storm is generally held to be due to the emission of some form of electrically-charged particle from the sun in great quantities, the particles often being emitted in a restricted direction. In their paths from the sun such particles may come into the earth's magnetic field, where they are constrained to move in spiral paths towards the magnetic poles ; they then act as electrical currents which distort the normal magnetic field of the earth and disturb the compass.

It does not follow that the electrified particles would reach the earth's atmosphere mainly above the magnetic poles ; for the earth's magnetic field is weak at very high levels, and the stronger field below, which still exists well above the ponderable atmosphere, would direct many of the corpuscles so that they would effect a ring around the magnetic poles. This may explain why, as a rule, cyclones

are formed some distance from the magnetic poles and circulate around them.

The average time between the meridian passage of a sunspot and the commencement of a magnetic storm is about 30 hours, and if the effect on the needle is immediate when the electrified particles reach the earth, their velocity as they pass through space would be about 860 miles per second. However, as it is probable that the electrified particles that cause the magnetic storms leave the sun about a day before the point from which they were emitted reaches the central meridian of the sun, it is likely that their velocity is less than the figure named.

Although sunspot and terrestrial magnetic phenomena show cycles of change which agree well with each other when long periods of time are considered, when the daily changes are compared the agreement is not so satisfactory. In the case of weather changes, other than seasonal or secular, no really satisfactory connection has hitherto been found to exist between them and sunspot periods.

The facts of Meteorology are of a very complex character and do not admit of easy classification. For example, some winds cause warm dry summers and cold dry winters, if they persist, whilst other winds, if they persist, result in cool wet summers and warm wet winters. On another page the question of the correlation of meteorological and sunspot phenomena will be considered.

That electrified particles from the sun, caught by the earth's magnetic field and directed towards the poles, might influence the magnetic needle, is a reasonable hypothesis ; but it does not seem equally reasonable to suppose that they could appreciably influence the temperature of the atmosphere, unless their velocities were very great and their numbers very large. Still we have to admit that the polar low atmospheric pressures, and the presence of great cyclones in high latitudes in the winter, do necessitate high temperatures locally in the upper atmosphere in high latitudes.

Of recent years the activities of the sun have been regarded in a new light. This has been found to be necessary owing to the production of proof that the earth must be more than two thousand million years of age. If the sun's heat were due to the most intense chemical activity we are aware of, and the whole mass of the sun were involved, the heat produced would not maintain the sun's output of energy for more than three thousand years. We must, therefore, recognise the fact that the matter of which the

sun is composed has been and is now producing energy at least six hundred thousand times greater in amount, atom for atom, than any known chemical change produces on the earth. It is now considered that the energy is liberated owing to atomic disintegration ; but we are quite in the dark as to the nature of the processes involved, and also largely of the nature of the matter radiated into space. There is no reason to suppose, however, that the heat given out by the sun is wholly due to atomic changes below its surface ; such physical changes may be taking place on its surface as well.

There are two fluid states, viz. the liquid and the gaseous. In the liquid state, when not constrained, a substance may have a free surface, such as that of the ocean ; but in the case of a gas, if there are no gravity or other forces to prevent its expansion, it is capable of spreading out without check in all directions. Although this is the case, whether a substance is in the gaseous or liquid state depends upon the temperature and pressure to which it is subjected ; for there is a critical temperature and pressure for each substance, below which it must be considered a liquid and above which it must be considered a gas. In the case of the sun the temperature is considered to be so high that the greater part of its mass is in the gaseous condition. However, this may not be the case with the matter forming sunspots—indeed their condition may be that of a very viscous liquid or even of a soft solid.

For a mass of matter deep below the sun's surface to rise, it must be distended by the formation of light gases, probably of radioactive origin. As the mass of bubbles and neighbouring dense gas rises, it expands adiabatically, cools, and becomes very viscous or even a soft solid. From such a mass when it reaches the sun's surface the gas would escape, as it has been observed to do, in the form of rockets or bright jets. Such would not be the case with gas escaping from the surrounding hot gaseous matter of the photosphere ; in this case the gases would generally rise as comparatively low-pressure bubbles, and make something resembling a splash, rather than produce a rocket or jet form of prominence.

We have seen that the photosphere is that portion of the sun above which it is transparent, the photosphere itself being incandescent. Now the masses of cool matter which rise from great depths in the photosphere, and which rise high enough to reach the upper incandescent surface, become visible there. Such masses as do not reach the surface

and are not seen, must however also give off jets of gaseous material. Indeed it may be that we see only a small proportion of the rising masses when the sun is very active.

The phenomenon known as the "umbra" thus appears to be due to that portion of the cool mass above which there is no incandescent gas, and the "penumbra" due to an overlapping thin portion of the incandescent photosphere through which the dark spot is seen.

Sunspots do appear to be the bottoms of cavities in the sun's surface. Father Secchi, who measured their apparent depths, states that in every case the depth found fell short of 4,000 miles, and averaged about 1,300 miles.

It would appear that we are not dealing with masses of matter floating on a surface of discontinuity, but rather cool masses floating near the upper limit of the incandescent photosphere.

From the foregoing considerations it would appear that gases escaping from spots may be considered likely to possess velocities sufficiently high for the matter to reach positions from which light waves could hurl them into space, and they would then form small clouds or pencils of tenuous matter.

There are, as already stated, prominences which are not in any way connected with sunspots, and these may throw out matter at velocities which, with the aid of light pressure, would cause the particles to pass into space. Indeed we shall see that when sunspots are absent or rare, there are still signs of variable heating at great heights in high latitudes over the earth, but that when sunspots are numerous and large they show a reasonably good correlation with pressure ranges on the earth.

Prominences can safely be regarded as existing above sunspots when they are young ; but it is doubtful in the case of large spots if very much gas is given off when they have commenced to decrease in size. However, when there are no visible sunspots, there may be cool masses of matter, which do not rise quite high enough to become visible, but which on account of their compactness send out high-velocity gas in the form of prominences.

There is a considerable volume of literature dealing with the correlation of sunspot periods with terrestrial periodic phenomena. Much of it refers to matters with which the meteorologist is not concerned, or is of an unconvincing character. Nevertheless there are magnetic and auroral phenomena which have been shown to vary in unison with sunspot phenomena. Some of these will be considered.

On Fig. 130 the curve *A* for sunspot frequency is calculated by Wolf's method ; *B* gives the compass declination, *i.e.* the variation in its diurnal range ; whilst *C* represents the diurnal variation of the horizontal magnetic

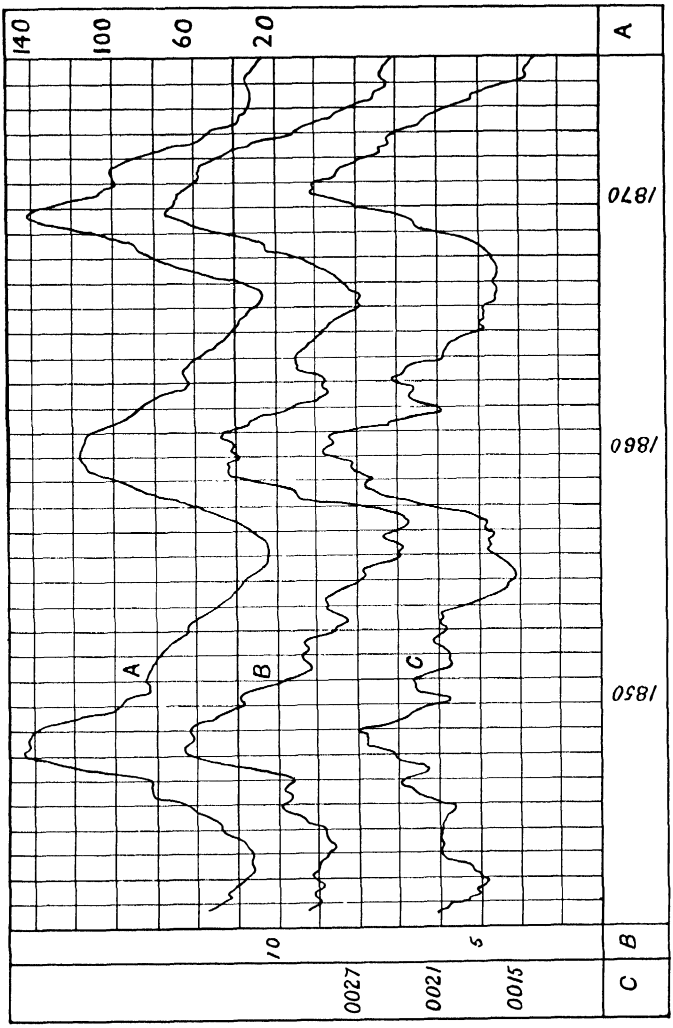


Fig. 130.—Correlation Curves for Sunspot Frequency and Magnetic Elements (After Spencer Jones).

force. These curves are in very close agreement, and we can safely conclude that the terrestrial phenomena concerned are caused by electrified corpuscles emitted by the sun.

A close relationship has also been found to exist between Wolf's relative sunspot numbers and the rise and fall of the water level in Lake Victoria, Lake Albert and Lake Nyassa, in equatorial Africa. This is clearly shown in Fig. 128 for the case of Lake Victoria.

A rather remarkable relationship between sunspot cycles and trade fluctuations may be referred to here. The Board of Trade publishes annual figures showing the number of passengers, and millions of tons of goods and minerals, carried each year by the Railways of the United Kingdom. The figures for passengers carried have been plotted on Fig. 131. It will be noticed that the curve does not rise quite regularly, as the railway traffic grew—as a result, mainly, of the steady growth of the length of the lines opened for

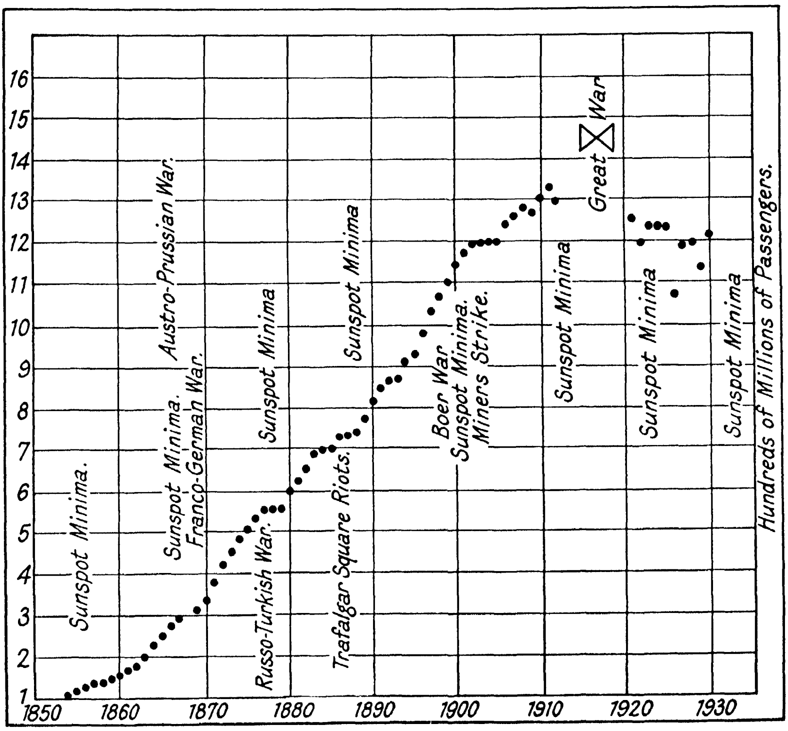


Fig. 131.—Variation of Railway Traffic Returns with Relative Sunspot Numbers, etc.

traffic. The irregularities shown by the curve resulted from the alternations of bad and good trade, and it will be seen that the increase of traffic returns is interrupted at times when sunspots are fewest. The dates of great wars and some labour troubles are also shown.

Such successes as have been attained in correlating sunspot periodicities with terrestrial periodic phenomena have been achieved by the comparison of secular phenomena. However, sunspot numbers vary periodically from day to day and month to month, as well as in a secular manner,

and if there is really any connection between meteorological phenomena and sunspot numbers it should be possible to show that it applies to the minor daily and monthly periods, as well as the long or secular ones.

The annual sunspot activity numbers are each the mean of those found for all the days of the year, and their usefulness for annual comparisons does not prove that they are individually useful. The only way to ascertain if Wolf's numbers are useful for daily purposes as well as annual ones is to compare them with some pronounced periodic meteorological phenomenon, and for this purpose mean pressures and pressure ranges can be used.

The publication of the new Daily Weather Charts renders it possible to make such a comparison, for these charts demonstrate that there are large areas on the earth which suffer considerable short-period variations of pressure, and also of pressure range, and these terrestrial periodic variations have time-intervals whose lengths are of the same order of magnitude as the short sunspot periods. On this account it appears likely that a daily as well as an annual agreement exists.

Wolf's sunspot numbers are given in Table XVIII for the years 1856 to 1921, whilst in Figs. 87 to 94 *A* are the smoothed Atlantic Area Mean Pressure curves, *B* the smoothed Atlantic Area Pressure Range curves, and *C* the smoothed Wolf sunspot numbers for each day of the years 1929 to 1932 inclusive.

To illustrate how the magnitude of the Wolf monthly mean numbers varied during the four years 1929–1932, Fig. 132 has been drawn. During this time an approach was being made towards an epoch of minimum sunspot intensity. On this account the phenomena exhibited by these years are of considerable interest, for they enable us to compare the year 1929, when sunspots were moderately numerous, with the year 1932, when they were scarce. On this diagram "faculæ" or "flocculi" numbers have also been plotted. To understand these we must study the "corona" a little more fully.

The general form of the corona has been found to vary with the sunspot cycle in a very marked way. During a time of sunspot maximum it is compact, without very long streamers, and more or less uniformly distributed around the sun's disc. On the other hand at a time of sunspot minimum, from the equatorial zones stretch curved streamers reaching to great distances. From this it is clear that even during a sunspot minimum the sun is active, throwing out

matter to great distances. That the prominences or streamers are material particles has been ascertained from the fact that much of their light, seen when the sun is eclipsed, is reflected sunlight.

It is now possible by spectroscopic methods to see the prominences, especially when they are near the sun's limb, when the sun is not eclipsed. Certain hydrogen and calcium lines in the sun's spectrum are found to be comparatively bright instead of dark, and it would appear that these bright lines are due to incandescent matter thrown to great distances into the chromosphere.

The *Astronomical Union Bulletin*, already referred to, gives character figures for the bright hydrogen flocculi and

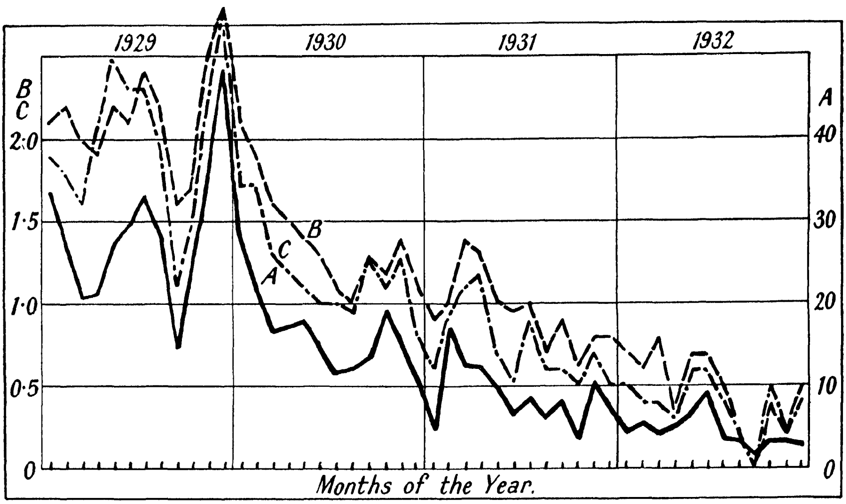


Fig. 132.—Monthly Means of Wolf Sunspot Numbers (*A*) and Character Figures of Calcium (*B*) and Bright Hydrogen Flocculi (*C*).

also for the calcium flocculi obtained by spectroscopic methods, and their mean monthly values have been plotted on Fig. 132, curves *B* and *C*. It will be seen that the three curves *A*, *B* and *C* largely wane and wax in unison, all three phenomena being due to some common cause of a periodic nature.

Flocculi are incandescent clouds, having a high temperature and floating in the chromosphere well above the photosphere. To maintain their temperature important atomic changes must be taking place in them, possibly similar to those which maintain the heat of the photosphere.

It is possible, however, for these three phenomena to be absent, or negligible in magnitude, but their "common cause" may still be throwing out corpuscles to affect the earth

to some considerable extent. But even if such be the case, sunspot phenomena should still be useful as an assistance in forecasting weather, especially if there is a considerable lag between the cause in the sun and the effect on the earth.

Before discussing solar phenomena further we will, for the moment, return to the question of terrestrial pressure ranges.

Curve *D* of the chart of Fig. 89 shows high- and low-pressure conditions over the Arctic area covered by the Daily Weather Charts during the first six months of 1930. On Fig. 123 the high-pressure conditions in high latitudes are marked by anticyclonic conditions near the North Pole, the pressure range being 20 mbs. In the case of Fig. 124 the high pressure over the Polar area has fallen from 1028 mbs. to 1012 mbs., and the low-pressure area over the North Sea has given place to a well-marked cyclone having a pressure of 996 mbs., the pressure range for the area being 28 mbs. (see Fig. 124 for pressure range). Now the pressure conditions of these two charts are quite different, but the pressure ranges do not differ as greatly as might be expected.

Such changes of pressure are responsible for climatic variations of a very pronounced character. Referring to this matter, Sir Napier Shaw remarks:—" All these show that there are small but important fluctuations of climate always in operation which can be included under the general description of changes in the general circulation of the atmosphere." He then continues:—" We shall be in a very much better position for studying this question when we have made out a satisfactory account of the general circulation of the atmosphere as it exists at present and the true meaning of what we have here called a change in the general circulation." (" *Manual of Meteorology*," Vol. I., page 91.)

In the present work an attempt is made to show that the small but important fluctuations in the general circulation are very largely if not wholly due to changes of pressure in high latitudes, where cyclonic and anticyclonic conditions alternate in a secular as well as short-period manner.

It is clear that if the pressure ranges were calculated for each day over the whole area north of 60° latitude it would have only little significance from the point of view of weather phenomena. To avoid as far as possible the pressure range being large when the mean pressure is high the pressure ranges adopted have been calculated for each day for the Atlantic Area (Fig. 85), which largely avoids the

area occupied by the Polar Anticyclone to which high pressures are due. However, it does not quite accomplish this, for three of the 27 points from which the pressure range of the Atlantic area is derived are near the Anticyclonic Area, and on some occasions the anticyclonic conditions even affect middle latitudes and give rise to unusual pressure ranges.

It may be possible to select a more satisfactory area than the Atlantic Area ; but this area has proved sufficiently useful for the purpose under consideration.

For the purpose of ascertaining how the daily mean pressures and pressure ranges of the Atlantic Area during the four years 1929–1932 compared with each other during winter and summer the following plan was adopted. 120 days in June and 120 days in mid-winter were selected from the four years and the mean pressures and pressure ranges for each tabulated. The winter mean pressures were then placed in their order of magnitude, the pressure range being placed against each mean pressure figure. Finally the mean pressure figures were divided into eight groups of fifteen figures each and the mean pressures and pressure ranges of each group calculated. The summer figures were treated in the same way. Fig. 133, in which the ordinates are pressure ranges and the abscissae mean pressures, shows by the curve how the two pressure phenomena are related.

In a few instances, in each group, the pressure ranges and mean pressures did not agree well with each other ; but the mean curves on Fig. 133 demonstrate that the agreement is generally good.

It must not be lost sight of that the Wolf Sunspot Activity Numbers, with which the pressure ranges and mean pressures are here compared, are also empirical figures ; and we must bear in mind that large pressure ranges sometimes exist even when the pressure conditions are anticyclonic.

On Figs. 87 to 94 the Wolf sunspot numbers, the pressure ranges and the mean pressures for the Atlantic Area for 1929–1932 have been plotted. To cause them to exhibit a phase agreement it is necessary to put forward the dates of the Wolf sunspot numbers seven days. The necessity for this would appear to be due to the fact that the electrified corpuscles take more than a day to reach the earth, and that when they heat the air where a cyclone will eventually appear, it takes more than five days for the heated dome of air to form and spread, and produce low pressures, *i.e.* cyclonic conditions. The agreement is quite good for 1929.

A study of the curves shows that even when the Wolf sunspot numbers decrease much in magnitude, the pressure ranges, although less marked, are still of considerable magnitude. It would appear that when the size and number of sunspots fall off very considerably, the solar disturbances wane less markedly. This is in agreement with the fact that solar prominences are present even when sunspots are few in number and size.

Figs. 87 to 94 indicate that in very many cases when the sunspot curve is low and the pressure range curve high, the

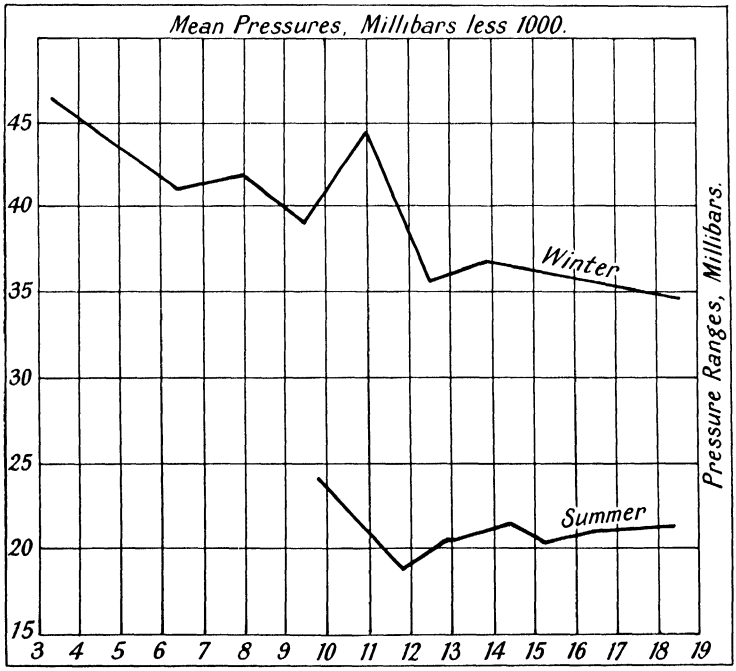


Fig. 133.—Correlation Curve of Mean Pressures and Pressure Ranges of Atlantic Area.

mean pressure is also high, the high pressure range curve being due to anticyclonic rather than cyclonic conditions.

Steady weather conditions, of whatever nature, obtain when large, comparatively shallow cyclones prevail. Under such conditions the precipitation of rain results largely from the presence of hills or mountains as a result of the flow over them of moist winds from the oceans. In low-lying areas rainfall is due mainly to the passage of secondary cyclones as they drift with the prevalent winds. Such secondary cyclones would appear to be most numerous when sunspots are most numerous.

A reasonably good correlation of Wolf sunspot numbers and Atlantic Area pressure ranges having been found for the year 1929, a careful examination of the Greenwich sunspot returns was made for that year, with a view to ascertaining if it is possible to calculate a sunspot number which is better in agreement with meteorological data. A good result was obtained when the following method was followed. The basis of the method is that the size, position and age of the spot or spot group are the main considerations. In the Greenwich returns all the necessary information for taking these data into account is given. The method tested is described below.

(1) In the Greenwich returns the sizes are given in millionths of the sun's diameter. These sizes were corrected according to the distance of the spot from the sun's centre, so as to give the apparent areas. This having been done, the square roots of these areas were calculated.

(2) All spots were found to have greatly decreased in activity after a life of seven days, and all spots known to be older than this were reduced to one-fifth the value stated in paragraph (1).

(3) When a spot first appeared on the sun's limb, and its area was decreasing, one-fifth value was taken.

(4) All recurrent spots, however large, were given one-fifth value.

(5) There was also evidence to show that spots are most active a few days before reaching the sun's central meridian, and they then decrease to about one-fifth value two days after passing the meridian.

Each spot or spot group having been treated in this way, the sunspot number for the day was taken as being the sum of the figures for each spot or group of spots.

The magnitude of the figures so obtained was such as to enable both sunspot numbers and pressure range numbers to be plotted to the same zero line.

The sunspot numbers so obtained gave a better correlation with the pressure ranges than did the Wolf numbers for 1929.

A very interesting feature of the pressure ranges is that they are most active during the winter. This is well shown by Figs. 87 to 94, and is due to the fact that great cyclones form in the Arctic regions during the dark winter months, with the result that mean pressures in high latitudes are lower during the winter than during the summer. Some meteorologists explain this by assuming that the air of these high latitudes is set in motion by some great dynamical force which reduces the pressure. However there is no

known dynamical force which could do this. Others assume that for some mysterious reason the heated air of the "horse latitudes" outside the region of the Trade Winds instead of rising and flowing towards the equator, hugs the surface of the earth for thousands of miles and moves north, and that when it finally reaches the Arctic regions it comes in conflict with the cold air of the north and the conflict results in great cyclonic activity.

The only reasonable theory seems to be that the air of the earth in high latitudes is heated by some agent other than the sun's heat rays, that the atmosphere then expands vertically, forming a dome over the heated centre, and that the air of this dome then flows away, towards the south in the case of the Arctic and towards the north in the Antarctic, and that as a result the pressure falls in high latitudes and the winds then blow in accordance with the dictates of the isobars.

It may be that owing to the position of the earth's magnetic field with regard to the sun during the winter, the field acts somewhat like a lens and directs the bulk of the corpuscles towards the magnetic pole most distant from the sun and fewer of them towards the magnetic pole facing the sun.

Some of the heating of the upper atmosphere is due to the interception of the sun's heat by the ozone layer; but, as has been pointed out, this is not sufficiently great to cause cyclones, representing only about five per cent. of the solar constant, and the heating would also occur where its effect would be of the wrong sign.

CHAPTER XIII.

PAST AND PRESENT CLIMATES.

As the earth derives practically all the heat it receives, either directly or indirectly, from the sun, it is natural that the question of the duration and constancy of the radiation should have engaged much attention. A hot body like the sun must be constantly creating fresh supplies of heat if it is to maintain a steady rate of radiation. Where does this heat come from ? Even now the question cannot be fully answered, but we do know where the storehouse is.

If the sun derived its heat from the most energetic chemical action known and this action involved the whole of the sun's mass, it could maintain its present temperature only for a few thousand years. Now there is good reason to suppose that the earth has been habitable by some form of life for something approaching two thousand million years, and it is clear that ordinary chemical combustion cannot have supplied the heat required.

Kelvin was of opinion that on the whole it was probable that the sun had not illuminated the earth for more than one hundred million years, and he regarded it as almost certain that it had not done so for five hundred million years. As for the future, he considered that we may say with equal certainty that the inhabitants of the earth cannot continue to enjoy the light and heat essential to life for many millions of years longer, unless " sources now unknown to us are prepared in the great storehouse of creation." We know now that this then unknown source is actually within the atom itself, but Kelvin could not satisfy himself of this in spite of the teaching of the geological record.

That the sun has had an ample supply of energy to provide all the light and heat that was required in the past, and still has enough energy left to make the earth habitable for hundreds of millions of years in the future, leaves the geologist free to study the story of the rocks, and to contemplate the past and the future without feeling cramped for time. It might be supposed that when the earliest-known rocks were formed the sun was hotter and the earth's climate warmer than it is now. However, we now know that throughout geological time the sun has maintained its

temperature at or near its present value, for in some of the earliest-known rocks we find evidences that glaciers and glacial periods existed even then.

All methods of measuring the age of the solid crustal portions of the earth are based upon the rate and magnitude of certain changes which are going on. Thus, if in the beginning of geological time the oceans were formed of fresh water, and rivers have been carrying salt into them in unvarying annual quantities, knowing the amount of salt in the sea and the amount added each year, it would be possible to calculate the age of the oceans. However, too many assumptions of a doubtful nature have to be made for the calculation to be reliable. Another method was based on the assumption that stratified deposits have been laid down throughout the past nearly at the same rate as at present, and on this basis it was calculated that the earth must be more than sixty million years old. Conclusions based on such premises as these must necessarily be unreliable, for we have no exact data to rely upon.

Owing to the discovery of radioactivity, much more reliable estimates can now be made. At one time it was thought that the atoms of the elements were quite stable, and this although there were reasons for believing that atoms were built up of numbers of smaller particles. However, it has been discovered that some elements, such as uranium, radium and thorium, are actually disintegrating, the resulting parts forming elements of lower atomic weight. The rate at which they thus automatically break up cannot be influenced appreciably by any known means ; for the highest temperatures and the greatest pressures we can command do not alter the rate of change.

Owing to the striking physical effects the break up of even one atom produces, it is possible to study radioactive changes even when very minute quantities are involved. It has been found that a sample of matter containing uranium loses half its radioactivity in 5,000 years, and this energy is again halved in another 5,000 years. It thus appears that the element, although continually breaking up into lead and helium, will never entirely disappear. Quite a few elements are thus found to be breaking up into lighter ones ; but there is no known case of any light elements spontaneously uniting to form heavy ones.

When crystals grow they enclose small quantities of uranium, an element which pervades all matter on the earth's surface, but such crystals seldom enclose lead or helium ; and if we analyse a mineral and determine the

amounts of uranium and lead present, we can determine how long ago it was consolidated, for the uranium slowly and steadily changes into lead and helium. Helium is generally left out of consideration, for it is a gas and some of it may have escaped. We may consider that when it was formed the mineral crystal enclosed a "uranium clock," and by analysis the chemist can calculate from the uranium-lead ratio how long any such "uranium clock" has been running and find its age in millions of years. The ages of the several formations, arrived at in this way, are given in Table XIX.

Our knowledge of the alterations that have taken place in the climate of the earth's surface during past ages has been derived from a study of the rocks. By rocks the geologist means deposits of sand, gravel, clay, limestone, coal, lava, etc., whether hard or soft. These have been formed by the destruction of still older rocks, and on this account the older rocks have suffered great waste and are largely covered up by more recent deposits.

A glance at a good map of England shows that it is made up of mountains, hills, valleys, dales and undulating areas of low relief, and that the rivers, as we follow them up from the sea, are formed by the union of lesser rivers and streams, which ramify as brooks into all the smaller dales and often begin as springs. In dry summer weather the water that flows down the river channels is almost all derived from springs and is clear and bright. But we must not suppose that it is then free from solid matter held in solution. The rain which fell and sank into the ground, to eventually appear in springs, was "soft," *i.e.* free from dissolved solids; but in its passage through the porous ground it dissolved certain solid substances such as limestone and gypsum, and the rivers carry these substances in an invisible form down to the sea. Such river water is, therefore, "hard," the "hardness" depending upon the amount of certain solids it contains. When all the rocks in a valley are nearly free from lime and other soluble material the river water is "soft." Where limestone rocks abound it is "hard."

It might be imagined that the quantity of rock so carried to the sea is small; but such is not the case. For example, the warm springs of Bath bring up with them each year material in solution which would form a nine feet square column, 140 feet high. And again the St. Lawrence spring at Lenk every year brings out of the ground over 2,000 cubic yards of sulphate of lime (gypsum). In this way great caverns are excavated. The immense amount of solid

matter carried out to sea in an invisible form will be appreciated when it is pointed out that the River Thames carries past Kew in solution about 550,000 tons of rock each year, mostly carbonate and sulphate of lime ; indeed about 8,000,000 tons of dissolved solids are every year removed from the rocks of England and Wales and carried into the sea.

The carbonate of lime thus carried away does not all remain in solution in the sea. It is taken up from the water by shell-fish and other forms of life. On the death of the animal the shells and other structures thus formed remain to a large extent on the bottom of the sea, and in course of time often build up beds of limestone or chalk hundreds or even thousands of feet in thickness and covering areas amounting to many thousands of square miles.

It is not only in this dissolved form that the rocks are carried to the sea. We know that during wet weather the rivers are discoloured with matter in suspension, and that stones and sand are continually carried along the river beds by rushing waters. The River Mississippi carries down to the sea each year in the solid form as much material as would form a pyramid 268 feet high and one square mile in area at its base. When we come to calculate the amount of material washed away from the land each year the quantity is found to be very great indeed. One foot of rock is thus removed from the whole surface of the British Isles each 9,000 years, and if we assume that the mean height of the land is 650 feet, then these islands might be planed down to the sea level in about six million years, a short period when compared with geological time.

We thus conclude that the contour of our hills and dales is due to the action of rain and running water. The softer rocks are carried away most rapidly, the harder rocks remaining as much-wasted hills and mountains, denudation being most rapid where the rainfall is great. It is as a rule in the early days of the denudation of a recently-raised area that the lines of drainage are initiated, and they then largely persist ; for the rivers exert a great eroding power on their beds, and with the aid of the stones and sand carried along, they cut through the harder rocks encountered. In the case of some rivers, such as the Colorado, mountain chains have risen in their paths, but they have maintained their courses by cutting gorges many thousands of feet deep right through the rising mountain masses. In other cases where great rivers, in some portions of their courses, have flowed rather near the coast, but have been separated

from the sea by high mountains, coastal streams have cut ravines through these mountains and captured the larger river, thus causing it to shorten its course. There is no more interesting study than that concerning the histories of rivers and valleys, histories which involve a study of Meteorology.

At one time it was thought that the amount of erosion along coast lines was comparatively small in amount when contrasted with the denudation going on inland, the belief being that marine denudation only affected coast lines to a small extent between high- and low-water marks. We now know that this is not the case, marine denudation being very active to depths of at least six hundred feet.

In an area like that of the English Channel, during south-westerly gales the surface water is driven with the wind towards the Straits of Dover, through which only a portion of it can pass. The rest sinks and moves towards the west as an undertow, carrying with it all the loose material on the sea bottom. It has been found that even at such depths as 600 feet, wrecks are broken up by the battering they suffer from quite large stones. During the Great War, when the sea was rough, those who were listening for the approach of submarines could hear the noise made by the commotion on the sea bottom. It is thus seen that the English Channel is being deepened as well as widened by the sea.

Practically all the material removed from the land is deposited in lakes, seas and oceans, and as it settles it covers up and preserves the remains of animals and plants that settle with it. Where the currents are comparatively strong the gravel and sand are deposited, and where the sea is comparatively quiet the finer material settles as mud on the sea bottom ; finally where the water is clear, warm and comparatively shallow, limestones are formed by the growth of molluscs, corals, etc.

In many seas the currents are variable, and they undergo changes of direction and force as the outlines of the continents and islands are changed by denudation. It thus results that beds of sand, clay, limestone, etc. alternate with one another.

It is clear that newer rocks have always been deposited on older ones, and in the absence of earth movements will always, if not washed away, remain in their proper relative positions as regards age. This fact has enabled us to ascertain what slow changes by process of evolution animal and plant forms have undergone from age to age. Such changes

have affected the earth as a whole, and it has been found possible to divide the rocks of the earth into formations of various ages. Table XIX indicates these several formations, the oldest coming first.

TABLE XIX.

Ages of Rocks.

Groups.	Systems.	Age in Years.
Proterozoic (Archæan)	Early	1,700,000,000
	Middle . . .	1,000,000,000
	Late	850,000,000
Palæozoic (Primary)	Cambrian	
	Ordovician . . .	375,000,000
	Silurian	
	Devonian . . .	300,000,000
	Carboniferous	
	Permo-Carboniferous .	220,000,000
	Permian .	
Mesozoic (Secondary)	Triassic	
	Jurassic	
	Cretaceous	
Cainozoic (Tertiary)	Eocene . . .	60,000,000
	Oligocene . . .	35,000,000
	Miocene	
	Pliocene	
Quaternary (Post-Tertiary)	Pleistocene, Gunz .	1,000,000
	,, Mindel .	450,000
	,, Riss . .	150,000
	,, Wurm .	50,000
Recent		

Now it is clear that if the rocks were stationary as regards height the land surfaces would soon all be washed down to levels below that of the sea. However, the solid crust of the earth is undergoing constant changes of level due to deep-seated changes which are at present little understood. In some places the land is rising and in others it is sinking.

The highest mountains are by no means the oldest. Indeed the Swiss Alps and the Himalayas are of much more recent age than many of our British hills—their fossils prove this.

Whatever the cause of the uplift which gives rise to land areas and mountains, it appears to be of a recurrent nature. This has become more and more apparent as the geology of the whole earth has become better known. The mountain-building forces would seem to act with great intensity for comparatively short intervals of time and result in the upheaval of masses and strips of land along the edges of continents, and over shallow sea areas where recent deposition of sediment has taken place. It has already been stated that such elevated areas float on the earth's crust, being the result of a decrease in density of comparatively deep-seated rocks.

In the case of most mountain chains there is a granite core, granite being a rock which was once in a molten state and has cooled down slowly. In many instances denudation has cut down the valleys so deeply into the mass of elevated land that this once molten rock is exposed. It is generally the case that the sedimentary rocks in contact with it have been considerably altered by the high temperature. Many geologists and physicists regard this heating as having been brought about by the disintegration of uranium and other radioactive elements deposited in the stratified rocks, with the resultant melting of the whole mass when not too near the earth's surface. Such heating would decrease the density and increase the heat of the rock below to very great depths. Whether the decrease in density thus brought about would be sufficiently great to account for the height of mountain chains we do not know for certain ; but it seems highly probable that it would be.

Now it is clear that denudation alone could not reduce such elevated areas to sea-level ; for as fast as material was removed from them by water, glaciers and wind, they would rise as a ship does when it is unloaded. Any estimate of the persistence of mountain ranges and plateaux thus involves a consideration of deep down density changes of the heated sub-crust which brought the mountains into existence.

We must suppose that the ultimate depression of these elevated areas results from cooling and shrinking, just as their elevation resulted from heating and expansion. It has already been shown that anticlynes would be caused by erosion along the bottoms of river valleys, which would result in the formation of a dome in the rocks below, and that there is no need to suppose that such undulations are

the result of a shrinking and cooling earth giving rise to compression of the crust. Indeed the discovery of radio-activity makes it doubtful if the earth is really cooling and contracting as rapidly as supposed.

Thus it does not appear that the persistence of mountain ranges can be calculated by appealing to denudation as the only factor involved. We have, for example, mentioned the case of the British Isles, and shown that denudation would bring them to the sea level in about six million years. If it be that the land rises almost as fast as it is carried away, we must regard the rate of escape of deep-seated heat as compared with its rate of production as being of greater importance.

The imperfection of the geological record of the older earth movements is very great, and any sound consideration of them is practically impossible. However, one of the great periods of earth movements is of comparatively recent date and has been closely studied.

At the close of the Cretaceous Period denudation and changes in the densities of deep-seated rocks had reduced the general level of the land to one of low relief. The rivers must have been sluggish and very free from sediment and dissolved material, and the seas generally shallow and clear near the margins of the continents. During such a period, except in such regions as the "doldrums," precipitation would be comparatively small, apparently no mountain ranges or elevated plateaux existing to raise the winds and bring down heavy rain. Secondary cyclones would be mostly confined to high latitudes, the dominant winds over the earth being those due to the circulation within the reduced area of the "horse latitudes" and the two much greater primary polar cyclones. The climates of high latitudes were warm, as the flora and fauna show. But it must be remembered that seasonal and day and night temperature differences would be very marked and the floras and faunas of high latitudes would differ considerably from those of low latitudes.

In the succeeding Tertiary Period the quiescence of Mesozoic times came to an end ; colossal earth movements took place, and the development of the present distribution of land and sea was initiated. The floors of the Cretaceous Seas were raised into low lands and the early Tertiary nummulitic sea was in places upheaved into a succession of giant mountains, some portions of the old sea floor being raised to a height exceeding 16,500 feet above the sea. These uprises mainly affected areas of previous great

and recent deposition, and it appears that the changes of density at great depths which cause each uprise are controlled to some extent by the presence of such recent sediments.

These great changes of land distribution and mountain building were completed before the oncoming of the last great ice age, which ushered in Pleistocene times. That the change of climate was not the result of the earth movements is proved by the fact that it was not a continuous period of cold. It consisted of four main cold periods, separated by warmer intervals. Even now the climate has not returned to the normal warm conditions of the earth.

Lyell in his "*Principles of Geology*" laid stress upon the effects that would result from changes in the position of land areas. Continents at the poles would be frigid, whereas if they were in low latitudes, and the polar areas covered by oceans, the earth at low levels would be practically free from frigid conditions in all latitudes.

What has been said about changing land distribution and elevation has been for the purpose of stressing the fact that great climatic changes are the result of meteorological forces, not geological ones.

We need not consider the great deposits of igneous rocks which are sandwiched between and thrust into sedimentary rocks, for they have no important bearing upon meteorological phenomena.

Our knowledge of the climates which have in the past dominated the surface of the earth has not been obtained entirely from a study of the forms of life they maintained, but also from the presence of peculiar glacial rock forms which are found sandwiched as it were between the water-borne rocks we have already described.

Hitherto only the rocks formed by running water have been considered. We must now notice those formed by ice sheets, glaciers and shore ice.

In cold regions during the winter the sea water freezes and the ice clings to the seashore as an ice foot or shelf. From cliffs stones fall upon its surface, and in its underside stones and boulders are firmly frozen. In the spring the masses of shore ice break up and drift out to sea, and as they melt the rocks they carry fall to the sea bottom. It thus comes about that rocks, which do not show any signs of wear, as do those in rivers or beneath glaciers, are carried long distances from their parent masses and embedded in sands and clays.

In such areas as the Antarctic Continent and Greenland, which are covered in many localities by immense sheets of

ice which slowly flow down the valleys in the form of ice rivers called *glaciers*, the ice often reaches the sea. As this ice slowly moves down the valleys it picks up fragments of rock of various sizes and rubs them against the hard and the soft rocks below. In this manner the surfaces of the rocks over which the ice moves are striated and polished, and striated and polished rock pavements are formed. The boulders held in the ice, and which act as graving tools to scratch the rocks below, are themselves also striated and polished. Sometimes one side only is flattened and polished ; but in many cases owing to the rotation of the boulder in the ice it is scored and polished all over. Streams of water also run beneath the ice carrying with them sand, gravel, finely-ground rock flour and clay. When such glaciers or ice sheets reach the sea or lakes these rock materials are deposited there, mixed together in all proportions—in one place sand and gravel, in other places sheets of touch clay full of glaciated boulders.

Glacial deposits are also laid down on land above the sea-level, often in lakes which have been formed in valleys the lower portions of which had a dam of ice across them. Thick beds of stiff clay and boulders are also formed beneath ice sheets as a result of their varying thickness and rates of movement. The material is torn up and pushed along in places where the erosion is great, collecting in others where the erosion is less severe. These deposits when dry are often exceedingly hard and difficult to excavate ; but when wet they form soft muddy masses.

Glaciers passing down valleys collect large quantities of loose angular material on their surfaces, and at the glacier end, where the ice melts, these rock materials are thrown down to form *moraines* of various kinds, and the issuing streams lay down thick sheets of coarse gravel known as outwash. In the neighbourhood of high mountains, where the erosion is greatest, the deposits are generally moraines of angular, subangular or glaciated stones ; but at long distances from the mountains they are almost always " tills " composed of boulders, almost every one of which is glaciated, the matrix being rock flour, or any adjacent soft rock, much contorted or reduced to fragments.

We thus have spread over the surface of the land in the British Isles and many other countries vast masses of glacial deposits, and these show that a great part of the British Isles has, in recent times, been buried almost wholly under ice sheets and glaciers.

One of the most noticeable features of a recently glaciated

country is the presence of erratic boulders, some of very large size. These often lie on the surface or are buried in glacial deposits. Such erratics were a great puzzle to early geological workers. They are often perched on hill sides or hill tops, and it was often found that they closely resembled the rocks of strata cropping out hundreds of miles away. In some cases they were seen to have been carried up valleys from low to high levels. It is now known that they were transported by ice, generally glacier ice.

The mode of formation of glacial deposits in past ages must be explained by any theory purporting to account for such changes of climate as have occurred. It is for this reason that a short account has been given of the nature of the deposits forming the geological record ; and it cannot be too pointedly urged that all such theories must stand the test of being considered from this point of view.

A distinction must be drawn between weather and climate. Weather types are the several factors which taken together constitute climate. Average figures are often illusory. This will be seen when we contrast Peking temperatures with those of the Scilly Isles:—

	A	B	C	D
Peking . .	53·1°	78·8°	23·5°	55·3° F.
Scilly Isles . .	52·2°	60·8°	45·3°	15·5° F.

(A) Mean annual temperature. (B) Hottest month. (C) Coldest month. (D) Temperature range.

In these two localities the mean annual temperatures are nearly the same ; but the annual ranges are very different. Thus the coldest month at Peking differs from the warmest by 55·3° F., whereas the range at the Scilly Isles is only 15·5° F. Similar marked differences will be found between one locality and another when annual and monthly means of rainfall, humidity, wind, sunshine or other factors are considered. The climates of two regions not far separated may also differ very considerably. Height above the sea, and aspect, are potent causes of such differences.

For a detailed consideration of past climates works on Climatology must be consulted. Only the salient facts which have to be accounted for are considered here.

An examination of the geological record shows that the rocks of most ages are free from signs of glacial action, and that throughout past ages life flourished from pole to pole for by far the greater portion of the time. Indeed the polar regions must have been many degrees warmer than they are now for at least 95 per cent. of geological time.

There would seem to be only two important factors of climatic change to be considered. The one is a change in the positions of continents and oceans, continents massed near the poles favouring cold climates, or when near the equator mild or hot climates. The other factor is a variation in the heating power of the sun's radiations.

If the polar conditions were generally anticyclonic, the surface winds of the earth would blow from the north-east in the Northern Hemisphere and from the south-east in the Southern Hemisphere, whilst the upper winds of the troposphere would move north and south from the equator as south-westerly and north-westerly winds. Under such conditions pressures over the "horse latitudes" would be greatly decreased, the high-pressure belt displaced towards the equator, and the whole of the earth's surface would be much colder than it is now, the warm winds flowing at high altitudes towards the poles.

However, if the lower winds blew from the equator towards the poles, owing to cyclonic conditions in high and middle latitudes, these winds, and the ocean drift they caused, would carry heat into high latitudes. The returning upper winds would be warmed by the sun as they approached the equator, and the earth's surface conditions might even be much warmer than they are now.

In low latitudes, between the equator and "horse latitudes," the flow is now of the surface cooling type, cold being carried towards the equator along the ground. In middle latitudes the flow is now somewhat of the warming type, the heat of the "horse latitudes" being carried along the earth's surface towards the poles. It is these latter winds that have been difficult to explain, for they flow from one to three thousand miles directly against the troposphere temperature gradient, but always of course in obedience to the pressure gradient.

There is no doubt but that with high pressures in high latitudes, owing to the lower dominant winds blowing towards the equator over the greater portion of the earth's surface, the rainfall would be less than it is now in high latitudes and greater in the region of the "horse latitudes." Over the high-pressure belts of the "horse latitudes" the rainfall is now

generally very small indeed, except in Asia during the Wet Monsoon. With high latitude high pressures the desert areas of the "horse latitudes" would largely disappear, for they would no longer be areas of descending air.

It must be remembered that the present heavy rains of equatorial regions result from the moisture picked up within the area occupied by the Trade Winds, and if these winds in Africa did not originate as they do now in desert areas, they would contain more moisture than at present.

Indeed, the great alteration in the general circulation of the atmosphere and the disappearance of the two high-pressure belts of low latitudes, would result in great changes in the rainfall and climate of many regions.

In low latitudes we have evidence of the former existence of pluvial periods. However the question of the rainfall in tropical Africa is so bound up with the Indian Monsoon conditions, and we have so little knowledge of the effect of high-latitude pressures upon the Monsoon, that it is unsafe to theorise upon past and present rainfall conditions in the African lake district.

Then again, C. E. P. Brooks has shown that the correlation between sunspot frequency and thunderstorms is good in low latitudes; this may be due to corpuscular emissions from the sun, where they strike the earth's magnetic lines of force at right angles in low latitudes, reaching the earth's atmosphere there, as well as near the poles.

At present it is not clear how the pluvial periods of low latitudes were related to glacial and inter-glacial conditions, but they would appear to be largely glacial condition phenomena.

It is often assumed that climate can vary only in sympathy with changes in the "solar constant"; but it will be seen that the direction of the dominant winds at the earth's surface is also a very important, and probably the most important, question for consideration.

Unfortunately the geological record of all past cold periods except the last one is very imperfect, and does not enable us to solve many of the problems we are faced with. However we will consider what light the geological records do throw on some of the problems that present themselves.

That high mountains are not always necessary for the initiation and growth of ice sheets during glacial periods is proved by the conditions under which these existed during the last or Quaternary Ice Age in North America. Here one of the centres from which the ice moved was over the Hudson Bay region. No matter how low the relief of the

land, if the snowfall exceeds melting and evaporation, ice sheets form. However in lower latitudes high land is more necessary. Thus when ice sheets formed over the low lands of North America, the Alps of Switzerland also sent down great glaciers which became confluent in the plains, but melted away long before they had spread far enough to reach the sea.

The Proterozoic rocks are the oldest known. Unlike those of succeeding ages no certain traces of either fossil, flora or fauna have been found in them. They have been much changed by heat and earth movements which have acted over long ages, with the result that their original structure has been largely obliterated. Such systems as they can be divided into depend entirely upon differences of structure, but it is generally conceded that they are largely old sedimentary rocks of one kind or other. The subdivisions recognised are purely local ones, no fossils having been found to enable rocks of apparently the same age in different parts of the world to be correlated.

The lapse of time considered to be represented by Proterozoic rocks is immense, the mean age of the earliest being about 1,700,000,000 years and the latest 850,000,000, the Archæan representing probably about two-thirds of the earth's geological history.

The " tillite " or consolidated boulder clay of the Lower Huronian (Lower Proterozoic) extends east and west in Ontario, Canada, for about one thousand miles, and 750 miles from north to south. It rests upon scratched or polished surfaces of older rocks, and some of the rocks have been brought from considerable distances. Signs of glaciation have also been noticed in the Archæan rocks of Western Scotland. At the time these glacial rocks were formed the relief of the land where the ice sheets formed may have been considerable, but it is not probable that elevated land areas were the cause of this early ice age.

The next period of glaciation recognised occurred immediately after the close of Proterozoic times and at the commencement of the Palæozoic Age. All the known deposits representing it rest upon Archæan and are covered in many cases by rocks of Cambrian Age. The " tillites " are very widespread, for they have been found in China, South Australia, India, South Africa and Norway. Their positions suggest that they were connected with cold conditions then existing in the neighbourhood of the poles, which would appear to have been in the same relative positions as regards the continents as they now occupy.

With the exception of certain deposits of Devonian Age there are no further signs of glaciation until late Carboniferous times are reached. The deposits of this age showing the existence of glacial conditions are most pronounced in South Africa.

The close of the Carboniferous period brought to an end a time of great mountain building, and the climate became cooler. In the early Permian glacial "tillites," striated boulders and ice-worn surfaces are found in north-west India, Tasmania, Togoland, Belgian Congo and South Africa. In South Africa the striæ show that they moved in a southerly direction, while in India they moved north. The widespread nature of the late Palæozoic glaciation has given rise to much speculation, it being considered improbable that glaciers reaching the sea could have been formed so far from the poles. The widespread nature of this glaciation, and its occurrence so near the equator, has been regarded as support to the theory of drifting continents. However even if we agree that such movements as those postulated by Wagener have taken place, other difficulties crop up quite as formidable or even more so.

It is admitted that many features of the climate we are now experiencing, such as the directions taken by the dominant winds, and the very great irregularities that occur in the march of the seasons, are not satisfactorily explained by current theories. In these circumstances it is unwise to maintain that during glacial periods certain phenomena could not occur, when it is clear that the theories relied upon also fail to explain present climatic phenomena.

An attempt has been made, in previous chapters, to show that during glacial periods there were higher pressures over the polar regions than now obtain, the sun's corpuscular emissions having been less intense. When there are high pressures over the polar regions the lower winds blow on the earth's surface towards the equator, carrying cold conditions with them. They then precipitate some of their moisture in the region of the "doldrums" and what are now the "horse latitudes." However, as these lower winds rise in low latitudes and move towards the poles and become chilled by radiation into space, further moisture descends as rain through the lower cold winds. Glacial conditions in high latitudes seem always to be accompanied by reduced precipitation. Indeed, there were regions in the far north, such as Siberia, in Pleistocene times, where, in spite of the intense cold, all the snow and ice that formed during other portions of the year disappeared during the summer,

owing to melting and evaporation. The cause of the high polar pressures at one time and low pressures at others we have attributed to changes in the solar corpuscular emissions. It would appear that throughout geological time low pressures and warm climates dominated high latitudes almost continuously ; but when the cause of these low pressures temporarily ceased to act, high pressures and glacial conditions supervened.

One of the most puzzling features of the distribution of glaciers during glacial periods is the intense sign of glaciation often found in low latitudes, where in many instances the glaciers evidently descended to the sea level, whereas in high latitudes, such as Siberia, even during the times of intense glaciation elsewhere, glaciers were absent. The matter would be more easily understood if during cold periods precipitation were small in high latitudes and great in low latitudes. But the weight of evidence favours the view that cold periods occurred when sunspot activity was small, and this appears to conflict with the evidence furnished by the variations of water level in the African Lakes, for in their case the precipitation indicated has been greatest when sunspots were most numerous. However the present variations of rainfall in Central Africa appear to be due in some measure to Indian Monsoon irregularities.

In the next chapter the glacial conditions which distinguished Quaternary times will be considered.

CHAPTER XIV.

THE QUATERNARY ICE AGE.

THE first indication we have in England of the lowering of temperature which ushered in the Quaternary Ice Age is the change which took place in the fauna and flora of the Pliocene deposits of Norfolk, Suffolk and Essex. In the case of the older ice ages our recognition of the fact that frigid conditions existed is due to the fact that on some horizons the rocks consist of consolidated boulder clays or " tillites," glaciated boulders and polished and striated pavements, the fauna and flora then existing furnishing little reliable evidence. However, in the case of the stages of the later glacial age we are considering, studies of the fauna and flora have greatly assisted in determining the sequence of events.

During Cretaceous times a luxuriant flora flourished in North Greenland. This flora included ferns, reeds, conifers, and such trees as poplar, oak, fig, walnut, laurel, magnolia, etc. In Miocene times in the same area we have beech, oak, poplar, maple, walnut and magnolia. In many instances the species were not such as we now know, but it is clear that such a flora could not now live in Greenland, and we are bound to recognise that the climate must then have been temperate or sub-tropical. The long dark winter was not cold enough to kill the plants ; and the long hot summer days enabled the flora to grow luxuriantly. In these northern areas the annual rings of growth are always much more marked than is the case when similar genera grow in low latitudes.

The appearance of boreal forms of shell-fish in the Newer Pliocene of the East of England and Belgium, some of which still live in northern seas, indicates that in the extreme north boreal forms must have commenced to develop a long time before cold conditions commenced to develop in England. Indeed there is evidence to show that the refrigeration of the Arctic regions came on and died away in waves of cold alternating with warmer intervals. We shall see that this last great ice age, the Quaternary, con-

sisted of not less than four well-marked glacial periods with more or less genial intervals, these four great waves of cold as they waxed and waned having superimposed upon them lesser waves. It is this irregular increase and decrease of the severity of each great glacial advance and retreat which often makes it difficult to decipher the records.

Each wave of ice as it advanced largely obliterated traces of previous glacial or mild conditions. In each locality as the cold increased the vegetation became more and more scanty, and disappeared almost completely before the ice overwhelmed the land.

In mountainous regions each successive ice sheet has almost obliterated the deposits of earlier ice sheets and of warm interglacial periods. In such localities we have only records of the last phases of the retreat of the ice. Our knowledge of the history of the Quaternary Ice Age at present really commences with the period of maximum ice extension. Some of the deposits lie outside all subsequent ice flows ; but they have suffered intense denudation, and only fragments of them remain. It is true that here and there their remains are to be found, beneath later boulder clays, etc., but they are often difficult to distinguish from deposits of later age. What took place as the cold waves grew in severity, and the glaciers advanced and partially retreated, we may never know in any detail. However, this portion of the history may be pieced together by studying the contemporary deposits of surrounding unglaciated lands, where the lake deposits, river gravels, cave deposits, etc., give much information concerning climatic changes. For example, in Africa the ice ages caused great changes in the rainfall, and we have exposed there lake deposits formed in depressed areas where only mere remnants of the former great lakes now exist.

The sequence of events which distinguished the culmination and disappearance of the great ice sheets of the Quaternary Ice Age were first clearly shown by studying such areas as Switzerland and Great Britain. When the history of the growth of our knowledge concerning glaciers and their work comes to be written, the great part played by our early British geologists will be found to be much greater than is recognised by many recent writers. Indeed, advances and retrogressions in the science of glaciology have in some respects been a reflection of the waxing and waning of the great glaciers themselves ; for it has often occurred that fairly correct explanations of the facts have been given, and then a new school of thought has come to the front,

with the result that new hypotheses have found favour whose chief recommendations have been their simplicity ; and these have been succeeded in turn by more correct views, generally as a result of the discovery of more reliable criteria.

It was early recognised that in England, Scotland, Ireland and Wales there were deposits of sand, gravel and stony clay of a very peculiar nature. No appeal to any of the then known denuding agents would account for them, and such practical working geologists as Hugh Miller were greatly puzzled. However, it soon became clear to those who had studied Swiss geology that the agent responsible was glacier ice.

For a knowledge of the great early advances made in the unravelling of the complex history of the British Isles we must turn to James Geikie's work, "*The Great Ice Age*," the third edition of which was published in 1894. Geikie showed that the Quaternary Ice Age consisted of at least four great cold periods separated by warmer intervals, and that there were several minor cold periods superimposed upon the four principal ones. Although the conclusions reached by Geikie are certainly in advance of those set forth in earlier publications, the general position maintained by him is the same ; and he considers that "it has become increasingly evident that during the Glacial Period cold and genial conditions alternated, and that man then lived in Europe." Writing in 1894, James Geikie remarks, "When some years ago I informed Albrecht Penck of the conclusions to which my examination of the glacial deposits had led me, it was with no small satisfaction I found that he had arrived at similar results from his investigation of the Swiss Alpine Lands."

However about this time there came to the front a school of glacial geology which maintained that there was only one cold period. It was also contended that glaciers had little excavating power, and could not appreciably erode valleys or excavate rock basins. Indeed it was said that a short cool period which the earth had suffered had been magnified into a glacial nightmare, and there were even those who revived the old theories that great floods from the oceans had swept over the continents and produced the so-called glacial deposits.

This set-back in glacial geology lasted for more than a generation, and for the time being some of the best work done by our older British glacialists was discredited. However, in America and the continent of Europe much good work continued to be done, and with the aid of the magnificent

memoir "*Die Alpen im Eiszeitalter*," by Albrecht Penck and Eduard Bruckner, the monoglacial theory may be said to have been ultimately relegated to the background, and all that James Geikie, Andrew Ramsay and others stood for has again come slowly to the front.

The glacial deposits of the British Isles are very difficult indeed to decipher. This is due largely to the insular position of the area and the presence to the north-east of the elevated Scandinavian Peninsula. In the Swiss Alps we have an area drained by several great rivers. During each cold spell of the Quaternary Ice Age these valleys were filled with ice, which spread over the surrounding plains, and became confluent there, but did not reach the sea. These conditions largely stabilised the growth of the ice sheets, and to a large extent confined them to particular areas. In America and the British Isles this regularity is much less marked, for the centres of dispersion moved great distances as the ice sheets waxed and waned, and this resulted in a very complex series of deposits being formed.

That James Geikie should have reached such a close approximation to the truth in such a difficult district to decipher as the British Isles is a standing monument to his ability. Nevertheless, although he arrived at practically the same general results as did Penck and Bruckner in the Swiss Alps, glacialists find it much more easy to understand the Swiss deposits than the British.

The criteria available for separating the deposits of one glacial period from those of another are the same whether we are dealing with a mountain mass surrounded by plains and foot hills, and far from the sea, or less elevated regions like the British Isles. However, in the former case we have great river valleys, which have been again and again glaciated in much the same manner, whereas in the latter we are dealing with an area of largely low relief which was flooded by ice originating in several not very elevated mountainous regions, sometimes one elevated region being the greatest centre of dispersion and sometimes another. In Switzerland the glaciers and ice fields of each cold period behaved in a much more regular manner, except as regards extension (for the four cold periods were not of equal severity).

Some space has already been given to the question of denudation by rain. It is also necessary to deal with denudation by ice, for there are several meteorological problems the exact nature of which cannot be properly understood without taking this course.

Geology alone can tell us what climatic changes have taken place in the past, and any theoretical explanation of such changes must agree with the facts geology discloses. It is not merely a question of how changes of climate might have been produced. We require to know how such climatic changes as the geological record shows us did occur actually did come about.

A large area, such as that occupied by the Swiss Alps, throws out in various directions great rivers, valleys and rock ridges. The elevated areas at the heads of or bordering such valleys often rise above the snow-line, and when this is the case the snow collects until the thickness is sufficiently great for it to run down the slopes into the valleys and melt there. Here it very often forms thick masses which slowly move down the valleys as great rivers of ice. These, as we know, are called "glaciers." Their size depends upon two factors, one being the temperature of the atmosphere at various heights and the other the amount of precipitation, either in the form of snow or condensation in the form of hoar frost and ice. A lowering of temperature brings an increasing area of the mountains within the region of cold, and an increasing snowfall results in an increased thickness of the ice, and, therefore, a more rapid flow of the glaciers. On this account there have always been two schools of thought, the one contending that increased glaciation has been due to increased precipitation, and the other favouring decrease of temperature as the cause.

Penck and Bruckner point out that the indications in the Swiss Alps the rocks give of the thickness of the ice in past glacial periods, as compared with the thicknesses in elevated areas at the present time, do not support the idea that greater precipitation there was the cause of the last glacial periods.

There is nearly always distinct evidence as to where the upper level of the snowfield was situated during glacial periods. Where the ice was thick and rested upon slopes, it was in constant movement downwards, and smoothed and wore the rock surfaces. Above this level we have projecting rocky serrated ridges and slopes. In the existing higher snowfields the present upper levels are not separated from the rocky serrated crests by smoothed rock surfaces. This shows that the precipitation is now as great as it ever was, or is even greater. Indeed the present snowfields do not part company with the rocky ridges until quite low levels, comparatively speaking, are reached. The highest levels of the old ice sheets and glaciers can almost everywhere be seen among

the mountains by the abrupt change from rounded to rough rock crests.

In some localities Penck and Bruckner have found evidence favouring the belief that when the glaciers reached their maximum extension the precipitation must have been less than it is now. But we must not suppose that this was everywhere the case, for there seems little doubt but that the changes in wind directions and the movement of climatic zones had the effect of increasing the precipitation in some few areas and decreasing it in most others.

A decrease in temperature of the earth's surface would certainly result in decreased evaporation from the seas and less precipitation, and it is most important to find that the changing levels of the Swiss Alpine glaciers and snowfields indicate a decreased precipitation and therefore a probable lowering of temperature. As a matter of fact a study of glacial geology shows that in very many instances a fall of temperature and dryness often do go hand in hand.

There are many varieties of glacial deposits, some formed beneath the ice sheets and glaciers themselves, others upon the ice near the land margins, and as the glaciers move down and melt away the rough material is deposited on the land or in the sea. Then we have the fluvio-glacial gravels thrown down in the great river valleys beyond the areas invaded by the ice sheets. Since we are interested only in the meteorological aspects of the matter, few of these can be mentioned. We shall, therefore, only deal with some of those which throw light upon the climate of the Quaternary Ice Age and indicate that it consisted of at least four major cold periods with intervening warmer ones and preceding and succeeding less severe periods.

When a great area such as that of the Swiss Alps and large surrounding areas occupied by foot hills and valleys is covered with ice, the erosion that takes place in the valleys is very great indeed. It is not merely that the rocks are ground away by the abrading sand pressed over them, or by boulders held in the ice and used as graving tools ; the ice actually freezes in places to the rocks upon which it rests, plucks out rock masses and carries them along. It is well known that the freezing-point of ice varies with the pressure to which the ice is subjected, and when, owing to irregularities in the surface over which the ice is moving, the pressure is relieved, the rock and ice freeze together, and either the rock is torn up or the ice ruptured.

Although the internal heat of the earth is, for most purposes, a negligible quantity, the actual amount of heat coming to the earth's surface each year is sufficient to melt a layer of ice 0·644 centimetre thick. Then again as the ice moves downwards its internal viscous friction is considerable and much heat is developed. Thus for about every 780 feet of descent one unit of heat is developed in each pound of ice, and if the ice be at the melting-point a portion of the glacier is melted internally. In the summer especially, the sun's heat is great and the ice is melted practically over its entire upper surface during the day, the water formed penetrating crevasses in the ice and reaching the bottom of the glacier. We thus have a quantity of water circulating below the ice, and this carries along with it waterworn stones of all sizes together with sand and rock flour. At the end of a large glacier this water issues from a large ice cavern and brings out with it more material in suspension than the river can carry away. Such a glacier stream is continually blocking its water course with gravel, and then moving to fresh positions near by. In this way it forms an ever-thickening mass of gravel and sand in the valley. Such deposits are known as "fluvio-glacial" deposits. They are coarsely or finely false bedded, have numerous large boulders in them, and may be hundreds of feet thick. Occasionally they wholly or partially bury large masses of ice separated from the front of the glacier, and as this ice melts away the gravel settles and its bedding is destroyed or contorted locally.

Where such glaciers terminate we have great boulders and all kinds of rock débris, which has fallen upon the ice from cliffs, thrown over the glacier front upon the fluvio-glacial gravel or on the valley sides, and this material forms ridges called "moraines" which often run parallel with the ice front. In some cases these moraines are of immense size. For example, the great moraine of the Dora Baltea in Northern Italy, opposite the mouth of the great valley of Aosta, has a frontage of about fifty miles, and its summits rise from 1,500 to 2,000 feet above the plains of Piedmont.

In the Swiss valleys four such sheets of fluvio-glacial gravel have been mapped by Penck and Bruckner. They all terminate in the regions of moraine formed by the four ice sheets at the time of their greatest extension. The four cold periods they indicate are as follows:—

Gunz Glaciation	Riss Glaciation
Mindel ,,	Wurm ,,

The ice of the Gunz glaciation, as shown by its moraine, in many instances extended further from the mountains than any of the subsequent glaciations, and resulted in the outspread of fluvio-glacials in most of the great river valleys draining the area.

Fig. 134 is a section across the Inn Valley at Scharding, in Upper Austria, a little distance above its junction with the Danube. The river drains the extreme eastern portion of Switzerland, and shows all the fluvio-glacial terraces on its valley sides. *G* is the Gunz outwash, *M* the Mindel outwash, *R* the Riss outwash and *W* the Wurm outwash. How deep the valley was when the Gunz gravel was deposited the section does not show; but it was probably almost as wide as the valley shown in the section. When the climate ameliorated and the glaciers retreated, the River Inn was

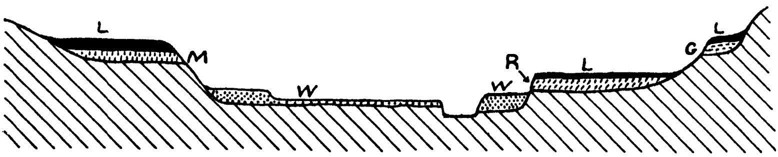


Fig. 134.—Section across Inn Valley at Scharding.

G, Gunz Outwash ; *M*, Mindel Outwash ; *R*, Riss Outwash ; *W*, Wurm Outwash ; *L*, Loess.

less burdened with material, and commenced to cut down through the fluvio-glacial material, deepen its valley and deposit ordinary river gravels. Such intervals must have been long ones, for the denudation the valley suffered before the oncoming of succeeding cold periods was very great indeed. Almost all the estimates of interglacial time have been based upon this consideration.

In Fig. 134 the Mindel outwash is on the opposite side of the valley to the Gunz and a vast amount of material must have been removed in Gunz-Mindel times.

The Mindel outwash was in its turn largely removed by ordinary river action, and when the valley had been much deepened the climate again became cold and the Riss outwash collected, to be in turn partly removed. In the valley thus deepened the Wurm outwash was deposited, through which the River Inn has since excavated the comparatively narrow post-glacial valley.

To the meteorologist the most interesting deposit is the loess, *L*, which is shown in Fig. 134 as resting upon the

three older fluvio-glacial gravel terraces. To make the importance of this deposit clear it will be necessary to describe the conditions under which it was formed and note some of its peculiarities.

It has been shown that well-watered land surfaces suffer much denudation owing to the action of rain and running water. However, the denudation would be much more rapid if it were not for the vegetation which springs up and conserves the soil. But denudation of another kind takes place in areas where the rainfall is markedly seasonal and a considerable part of the year so dry that vegetation such as grass disappears. In such cases the winds sweep the fine earth and sand along the ground, and by sand blast action reduce much of it to such fine dust that it is picked up by the winds and carried thousands of miles. The amount of dust which is thus put in motion by the wind reaches enormous proportions. Even now in Northern China and Central Asia dust storms at times conceal the sun for days in succession and a fine yellow sediment of measureable thickness settles after every storm over large areas of country.

As a rule the areas from which the dust is removed, as well as those where it is again deposited, are more or less arid; dust is also rapidly brought down in areas where there is considerable rainfall by the condensation of moisture on the dust particles. In dry areas where dust settles it forms thick and extensive beds of loess, a deposit the characters of which are just such as would be expected when dust falls and collects where there is some vegetation growing.

In its typical form loess is a fine-grained deposit consisting of minute particles of mica, felspar, quartz, hydrated silicate of alumina and other minerals, the whole being more or less cemented with bicarbonate of lime. It presents a remarkable contrast to water-borne sediments, owing to its homogeneity of composition. Vertical tubes permeate it more or less completely, the tubes often being encrusted with carbonate of lime, and ramifying downward like the roots of grass. The tendency to vertical cleavage results in the formation of vertical "bluffs" where the material is now suffering denudation.

The distribution of loess is independent of altitude. In China it occurs at heights from a few feet above sea-level to 8,000 feet. In hilly regions it occupies depressions between the ridges, the surface rising on all sides up the hill slopes. Indeed it first drifts mainly into the minor valleys, slowly

fills them up until the minor ridges just rise above the surface, and finally obliterates all minor features and sweeps up the mountain sides.

The fossils found in the loess consist almost wholly of land animals, the shells of land snails being found evenly distributed throughout its mass. Much of the dust deposited upon the grass steppes of Asia, and retained there, is derived from the practically rainless deserts of the interior, where intense heating by the sun, and sand blast action on the rocks and pebbles, results in the formation and transportation of fine dust to less arid or calmer regions.

In Europe the loess extends in a broad belt from France and Belgium, through Middle Germany, eastwards to the northern slopes of the Carpathians, where it merges into the big loess plain of Podolia in Russia. We can thus trace it in Europe from the west, where it is no longer forming, to the east, where it is now being deposited in south-east Russia under steppe conditions. It is clear that when it was forming in Western Europe there were dry easterly winds carrying the dust from east to west. Occasionally even now, when easterly winds blow over the loess belt, rain and snow of a yellow colour fall in such localities as Silesia.

In Fig. 134 it will be noticed that the three upper terraces are covered by loess, the last or Wurm terrace being free from it. There were consequently several semi-arid periods in Europe during the Quaternary Ice Age.

It would be impossible here to discuss in any detail the exact relationship of the loess to the four great outspreads of fluvio-glacial gravels. However the following table exhibits the facts as they have been ascertained.

Wurm Glaciation ..	4th Fluvio-glacial terrace.
Interglacial	Loess.
Riss Glaciation ..	3rd Fluvio-glacial terrace.
Interglacial	Loess.
Mindel Glaciation ..	2nd Fluvio-glacial terrace.
Interglacial	Loess not very well marked.
Gunz Glaciation ..	1st Fluvio-glacial terrace.

It is clear that the loess is an interglacial deposit, and it is considered likely that it was formed during the Gunz-Mindel interglacial period, as well as in subsequent periods.

According to W. B. Wright, an interglacial period embraces three successive phases of climate in the case of the Swiss Alps:—

(1) A phase of valley erosion, and the filling up of many glaciated hollows.
(2) A phase of river valley erosion and the formation of river gravels.
(3) A phase of loess formation with dry steppe conditions.

This indicates that two of the four great ice sheets at least were ushered in by the oncoming of more arid conditions ; conditions which also involved the periods when the ice sheets were in existence, if the evidence furnished by the upper levels of the snowfields are taken into consideration.

It is interesting to note that there is no loess upon deposits of the Wurm period, and, therefore, so far we have no indication that the Wurm glaciation is to be followed at an early period by a fifth glacial period ; for such an event would be preceded by loess forming in Central and Western Europe.

At the present time Europe owes its moisture and temperate climate to the prevailing south-westerly winds. However, at times these winds cease to function, and Europe then experiences a dry cold spell. Now one of the difficulties of the meteorologist is to explain why these westerly winds blow at all ; for they travel for several thousands of miles against the surface temperature gradient. No help is furnished by assuming that they are due to the rise in high latitudes of the warm southern winds, providing energy for the production of cyclones. As a matter of fact cyclones often form over the cold Baltic area in winter, or even over North European Russia. They also often originate in the neighbourhood of Labrador and Greenland. Indeed, the temperature distribution in the troposphere in a cyclone is not the cause of the cyclone. The temperature distribution results from the movements of the cyclone and is generally slightly opposed to those movements. Accepted theory does not give us any clue as to why the prevailing south-westerlies of middle latitudes in the Northern Hemisphere exist.

Now we will suppose that the driving force which produces the actual circulation in middle latitudes ceased to function to some considerable extent, and that north-easterly conditions became the prevalent conditions over Europe. The result would be a much colder climate in Europe, a

decreased rainfall, and the existence of cool or cold steppe conditions over a great part of the Continent.

We are thus faced with the fact that the problem is not to explain why ice ages have existed ; for if it is the solar light and heat rays alone that are responsible for climate, then it is difficult to explain why the earth is now comparatively warm and habitable in middle or somewhat high latitudes. We really have to explain why the past history of the world has been a warm one for the greater portion of geological time, and this it would appear can only be done by assuming that it is the corpuscles thrown out by the sun that account for climates being as they now are and have been in past ages.

APPENDIX.

MEAN DAILY PRESSURES AND PRESSURE RANGES FOR 1929-32.

TABLE XX.

Smoothed Pressure Values for 1929—Atlantic and Arctic Areas.

Pressures in Millibars — 1000.

	January.			February.			March.			April.			May.			June.		
	Ar.	At.	P.R.	Ar.	At.	P.R.	Ar.	At.	P.R.	Ar.	At.	P.R.	Ar.	At.	P.R.	Ar.	At.	P.R.
1				24	13	42	14	13	34	13	15	24	16	15	23·	—	16	24
2				20	12	37	14	13	35	14	13	23	18	16	23	—	14	25
3	13	12	35	18	12	32	13	12	34	15	13	23	18	16	23	13	13	26
4	13	13	36	16	12	31	13	12	32	14	13	21	18	16	25	13	11	27
5	14	15	37	16	12	31	14	11	30	15	12	21	18	16	25	11	10	27
6	14	16	41	16	14	30	14	9	31	15	12	22	19	16	26	10	10	26
7	14	17	44	16	15	29	14	8	32	14	13	21	—	15	26	10	10	24
8	14	19	41	16	15	31	13	8	32	14	13	20	—	14	26	10	11	22
9	13	20	41	17	15	31	12	9	33	15	14	21	—	13	25	10	12	21
10	14	20	41	17	15	31	10	11	32	14	15	23	—	13	25	10	13	20
11	16	20	39	16	14	35	10	12	30	14	16	23	—	13	24	9	13	19
12	16	20	35	16	14	38	10	14	29	15	17	26	—	14	24	9	13	20
13	17	19	35	16	14	40	11	15	30	16	18	28	—	14	23	9	14	20
14	18	18	34	16	14	40	11	15	29	16	19	28	—	15	23	9	14	19
15	17	16	32	17	14	40	13	14	30	16	19	26	—	15	24	10	14	18
16	18	15	28	18	16	39	14	15	30	17	18	26	—	16	25	10	14	19
17	15	13	27	19	17	38	13	14	30	16	17	27	—	16	25	12	15	18
18	14	11	29	20	18	37	8	14	31	15	16	25	—	16	24	13	16	19
19	15	10	31	20	18	39	7	14	32	15	15	25	—	15	24	14	18	19
20	17	11	37	19	17	40	6	14	31	15	14	26	—	15	23	16	19	21
21	21	12	42	17	15	37	7	14	32	16	13	24	—	15	22	17	20	21
22	24	14	46	16	13	37	7	14	33	15	12	23	—	15	23	17	19	23
23	27	16	49	14	11	37	8	12	32	16	13	24	—	16	23	18	18	23
24	29	17	48	14	12	34	9	12	33	16	14	26	—	16	23	17	17	22
25	31	20	50	14	13	30	9	11	34	15	14	27	—	17	22	15	16	21
26	32	20	50	14	14	31	9	11	34	13	15	28	—	18	22	14	15	19
27	34	21	53	14	14	31	11	12	34	14	15	27	—	18	21	12	14	16
28	35	21	54	14	14	33	12	13	33	15	15	27	—	18	20	11	14	15
29	34	20	53				12	13	30	15	15	25	—	17	20	13	14	15
30	31	18	50				13	14	29	15	15	24	—	17	22	14	14	14
31	29	16	47				13	15	27				—	16	23			
Means	20·6	16·5	40·8	16·8	14·3	35·0	11·0	12·6	31·5	14·9	14·8	24·4		15·6	23·5	12·4	14·0	20·8

TABLE XXI.

Smoothed Pressure Values for 1929—Atlantic and Arctic Areas.

Pressures in Millibars — 1000.	July.			August.			September.			October.			November.			December.		
	Ar.	At.	P.R.	Ar.	At.	P.R.	Ar.	At.	P.R.	Ar.	At.	P.R.	Ar.	At.	P.R.	Ar.	At.	P.R.
1	15	14	14	9	11	20	15	14	19	5	9	33	9	13	36	8	3	41
2	15	14	16	9	11	20	16	14	20	5	8	31	9	13	37	6	1	43
3	14	14	18	10	11	20	16	15	20	5	8	29	9	11	37	5	1	47
4	14	14	19	11	12	21	17	15	19	4	8	28	9	10	36	3	0	50
5	12	14	20	12	12	22	16	15	19	3	8	26	8	9	36	4	0	50
6	12	15	20	12	12	21	14	14	19	6	8	24	8	7	38	7	0	49
7	13	15	20	11	12	21	13	14	19	8	9	24	5	6	42	8	1	46
8	13	14	20	12	12	21	12	13	19	7	9	27	5	7	41	9	0	45
9	13	14	21	11	12	20	11	12	20	6	10	29	3	7	43	11	2	44
10	13	14	22	11	12	19	10	12	22	7	11	29	4	7	45	12	3	41
11	12	13	23	10	13	19	10	12	24	7	11	29	4	8	43	13	5	39
12	12	13	23	10	13	18	10	12	26	6	12	28	6	8	37	13	7	38
13	11	13	23	10	14	18	9	12	26	6	13	26	9	8	33	13	9	38
14	12	13	22	—	14	18	10	13	26	6	13	25	9	9	28	13	11	38
15	11	13	21	—	15	18	9	13	28	5	13	24	15	9	24	13	12	37
16	11	14	19	—	14	18	9	12	29	6	14	25	15	9	22	12	12	40
17	11	14	17	—	14	18	7	11	30	7	14	25	17	10	24	11	12	43
18	11	15	16	—	14	18	6	10	33	8	13	24	18	10	26	11	11	44
19	11	16	14	—	14	18	6	10	36	9	12	26	18	11	28	12	10	45
20	10	16	15	—	13	20	6	10	34	10	10	29	17	11	32	12	9	47
21	10	15	16	—	14	20	7	10	33	9	9	33	17	12	36	12	8	46
22	8	14	18	—	14	21	10	11	34	8	7	37	15	13	37	11	8	45
23	8	12	20	—	14	21	12	12	32	7	5	39	13	13	37	13	8	45
24	8	11	20	14	14	21	13	13	29	6	5	37	11	12	37	—	8	47
25	8	11	20	14	14	20	14	14	29	7	5	35	10	11	37	—	8	44
26	8	12	19	14	14	19	13	14	29	8	6	31	11	10	37	—	7	39
27	8	12	19	13	14	18	11	14	28	9	6	27	12	9	36	—	7	37
28	8	12	19	13	13	17	10	13	30	11	8	27	11	8	34	4	7	38
29	9	12	19	13	13	16	8	12	30	11	9	30	12	6	35	6	8	37
30	9	12	19	13	13	17	7	10	32	10	10	33	11	5	38	6	8	38
31	9	11	20	14	14	18				9	12	35				7	9	40
Means . .	10·9	13·4	19·1	11·7	13·1	19·2	10·9	12·5	26·5	7·1	9·6	29·1	10·7	9·4	35	9·4	6·3	42·6

TABLE XXII.

Smoothed Pressure Values for 1930—Atlantic and Arctic Areas.

Pressures in Millibars − 1000.	January.			February.			March.			April.			May.			June.		
	Ar.	At.	P.R.	Ar.	At.	P.R.	Ar.	At.	P.R.	Ar.	At.	P.R.	Ar.	At.	P.R.	Ar.	At.	P.R.
1	9	8	42	15	9	35	10	10	40	9	6	36	10	12	19	16	18	21
2	11	8	42	16	10	34	10	11	39	9	8	37	10	14	19	15	16	22
3	11	8	42	14	11	30	9	12	36	11	10	36	12	14	19	14	15	23
4	12	8	41	13	12	27	7	13	35	13	12	32	12	15	20	12	13	24
5	12	8	42	14	13	26	6	13	35	15	14	29	13	15	21	10	12	24
6	11	8	42	14	14	28	4	12	35	16	15	29	14	15	22	9	12	26
7	9	8	45	12	13	33	2	11	34	16	15	27	15	15	23	9	13	24
8	8	8	47	12	14	37	2	10	34	15	15	26	16	15	24	9	13	24
9	8	8	48	11	13	40	3	8	33	14	14	26	17	15	23	8	13	25
10	8	7	50	9	11	43	4	8	31	14	15	25	18	14	22	8	12	27
11	9	7	48	8	10	44	6	8	31	15	14	23	17	13	22	8	12	27
12	10	7	44	7	9	43	8	8	31	17	14	24	16	12	21	8	12	27
13	13	9	41	7	9	40	9	8	30	18	14	25	17	12	20	10	12	26
14	15	11	37	8	9	38	10	9	29	19	14	25	15	12	20	12	13	23
15	15	11	34	9	10	41	10	7	29	19	15	26	14	12	21	13	14	22
16	15	14	36	8	11	43	12	9	28	20	17	28	13	14	21	13	14	21
17	14	14	39	8	12	42	14	10	28	20	17	28	11	13	22	13	14	22
18	11	13	39	8	14	43	15	10	29	20	17	28	11	14	21	13	13	21
19	10	12	43	8	14	40	15	9	31	19	17	27	10	13	22	13	13	21
20	10	10	43	8	14	38	16	10	32	20	16	26	10	13	22	12	12	21
21	10	10	41	9	16	34	16	11	32	20	15	26	11	13	22	12	13	20
22	11	8	40	11	17	33	16	12	33	21	15	27	10	14	22	12	12	18
23	11	8	39	13	17	32	16	14	29	22	16	30	13	15	22	11	12	18
24	11	7	37	14	18	30	18	15	27	23	17	30	14	15	22	10	11	19
25	11	6	35	14	16	32	19	16	27	22	18	29	15	15	23	9	11	19
26	11	6	34	15	14	35	20	16	27	20	17	24	16	15	24	9	11	19
27	12	7	33	13	12	37	19	14	28	18	16	23	16	15	25	9	11	19
28	13	8	32	12	10	38	18	12	28	15	14	20	16	15	26	9	11	18
29	14	9	34				15	10	30	12	13	19	16	16	26	10	12	18
30	16	9	36				12	7	33	10	12	19	17	18	24	10	12	17
31	15	9	36				10	6	36				17	18	23			
Means . .	11·5	8·8	40·1	11·1	12·5	36·3	11·3	10·6	31·6	16·7	14·4	27·0	13·9	14·2	22·0	10·9	12·7	21·9

TABLE XXIII.

Smoothed Pressure Values for 1930—Atlantic and Arctic Areas.

Pressures in Millibars — 1000.	July. Ar.	July. At.	July. P.R.	August. Ar.	August. At.	August. P.R.	September. Ar.	September. At.	September. P.R.	October. Ar.	October. At.	October. P.R.	November. Ar.	November. At.	November. P.R.	December. Ar.	December. At.	December. P.R.
1	10	11	18	12	13	16	16	17	17	13	18	22	10	8	32	8	9	43
2	10	11	20	12	13	16	16	17	17	13	18	22	9	7	32	5	9	46
3	9	11	22	11	12	18	16	17	18	13	16	22	9	6	34	5	9	48
4	10	11	22	12	12	21	17	18	19	12	14	23	8	6	35	5	10	45
5	10	11	22	13	13	23	17	18	18	11	13	26	8	6	36	5	11	41
6	11	12	22	13	13	21	16	17	19	10	11	28	9	7	37	5	11	35
7	12	13	22	13	13	21	16	17	19	13	10	30	7	8	39	7	11	30
8	13	13	22	14	14	19	16	17	19	13	10	32	7	9	40	7	10	31
9	13	14	22	14	14	18	15	17	18	10	11	35	7	11	42	8	9	32
10	14	15	21	13	13	19	15	16	19	9	11	32	8	12	42	9	8	34
11	15	15	19	13	13	21	16	17	20	11	10	30	9	12	43	11	8	36
12	15	16	17	12	12	25	15	17	19	12	8	29	8	13	42	10	9	36
13	15	15	17	11	12	25	14	17	19	13	8	31	8	13	40	12	10	36
14	14	15	18	12	12	25	14	17	19	13	8	32	6	13	40	12	11	37
15	13	14	19	14	14	24	13	16	18	14	8	33	5	14	38	12	12	39
16	12	12	21	15	15	22	13	15	17	14	8	34	6	14	33	12	12	41
17	11	11	20	17	15	19	13	15	17	13	8	34	8	15	31	12	12	43
18	11	11	20	18	16	18	13	14	19	12	9	32	8	14	30	11	11	44
19	11	10	19	19	16	20	11	12	19	10	9	30	10	12	31	12	13	43
20	11	11	19	18	15	20	12	12	19	9	10	30	9	9	32	14	15	38
21	11	11	19	16	14	20	13	12	20	9	10	30	10	6	34	14	16	34
22	10	11	19	14	15	20	14	13	21	8	10	29	9	3	36	15	16	29
23	10	11	19	13	15	20	15	13	22	8	10	28	7	2	37	15	16	25
24	10	12	18	13	15	19	15	13	22	8	10	27	10	2	36	15	13	26
25	11	12	17	15	16	17	16	14	23	7	9	25	12	3	36	12	11	29
26	11	12	17	16	16	17	15	14	23	9	10	27	12	5	35	11	9	32
27	12	12	17	16	16	18	15	15	23	11	11	24	12	6	36	9	8	35
28	12	12	17	17	16	18	15	16	22	12	11	26	11	8	36	9	7	36
29	12	13	17	16	16	17	14	17	22	13	10	27	10	9	38	9	7	36
30	12	13	16	16	16	17	14	18	22	14	10	29	9	9	39		7	36
31	12	13	16	15	17	18				12	9	30					7	33
Means . .	11·7	12·4	19·1	14·3	14·3	19·8	14·7	15·6	19·7	11·3	10·6	28·7	8·7	8·7	36·4	10	10·6	36·4

TABLE XXIV.

Smoothed Pressure Values for 1931—Atlantic Area.

Pressures in Millibars − 1000.	January. At.	January. P.R.	February. At.	February. P.R.	March. At.	March. P.R.	April. At.	April. P.R.	May. At.	May. P.R.	June. At.	June. P.R.
1	7	31	14	33	12	37	15	24	16	20	16	23
2	7	29	13	36	11	37	15	25	16	20	16	25
3	8	28	13	38	11	36	15	23	16	21	17	27
4	8	27	12	39	10	36	13	25	16	21	16	27
5	9	28	11	37	10	36	11	27	15	22	16	27
6	11	30	10	38	10	36	9	28	16	23	16	26
7	12	30	10	39	12	35	8	29	16	22	16	24
8	13	29	7	41	13	33	8	30	16	21	16	22
9	14	30	8	44	14	33	9	29	15	21	17	22
10	14	30	8	49	15	35	11	27	14	22	17	20
11	14	29	9	49	15	37	12	27	13	22	17	19
12	13	31	9	47	14	39	14	26	12	22	17	18
13	12	32	10	44	13	40	14	26	11	23	16	19
14	10	35	11	40	12	39	15	25	10	21	15	19
15	9	39	11	35	12	37	16	25	10	19	14	19
16	7	40	11	36	11	34	17	24	11	17	14	21
17	7	38	12	36	10	33	18	24	10	17	13	22
18	7	35	11	38	10	32	18	22	10	18	13	22
19	9	30	10	40	10	29	19	21	12	19	13	23
20	10	29	10	41	10	29	18	19	14	21	13	24
21	12	30	10	39	11	28	17	19	15	22	12	25
22	11	33	11	39	12	26	15	20	16	21	12	25
23	10	36	13	37	14	26	14	21	18	21	12	24
24	10	38	15	35	14	28	14	22	19	20	12	23
25	9	39	16	36	15	29	13	22	19	19	13	23
26	10	38	16	36	16	29	14	22	17	20	14	23
27	11	37	15	36	16	29	15	22	17	22	14	24
28	12	33	13	38	16	28	15	21	16	22	14	24
29	12	33			17	27	15	20	18	23	14	25
30	13	32			16	25	16	21	17	23	13	24
31	14	33			16	23			17	23		
Means . .	10·5	32·6	11·3	39·2	12·8	32·3	14·1	23·8	14·7	20·9	14·6	23·0

TABLE XXV.

Smoothed Pressure Values for 1931—Atlantic Area.

Pressures in Millibars — 1000.	July.		August.		September.		October.		November.		December.	
	At.	P.R.	At.	P.R.	At.	P.R.	At.	P.R.	At.	P.R.	At.	P.R.
1	12	24	11	20	15	20	10	36	12	32	11	43
2	11	24	11	22	14	20	9	37	10	38	9	45
3	10	23	13	22	15	21	8	40	8	41	8	44
4	11	21	14	22	15	20	9	41	7	41	6	43
5	12	21	14	21	14	20	9	38	6	41	6	42
6	13	19	14	21	14	20	9	35	7	37	7	38
7	14	19	12	21	14	21	10	34	8	35	8	35
8	15	21	12	20	14	21	11	34	8	36	10	34
9	14	22	12	21	14	22	10	35	7	37	10	37
10	14	22	12	21	13	24	9	36	5	37	10	38
11	13	23	12	21	12	24	10	35	4	39	11	38
12	13	22	13	22	12	26	11	34	3	38	10	37
13	12	18	13	22	10	28	11	33	4	35	11	39
14	12	17	13	22	10	29	12	31	7	35	12	35
15	13	17	13	20	10	29	13	31	10	39	12	34
16	12	17	13	20	10	29	14	30	13	39	12	36
17	12	19	13	19	11	30	14	30	15	40	12	37
18	13	21	13	18	13	30	14	30	15	42	11	36
19	12	22	13	17	14	29	14	31	15	45	13	37
20	12	23	13	18	15	30	13	31	15	46	13	40
21	11	23	13	19	17	32	12	32	15	46	14	40
22	11	22	12	19	17	27	11	31	14	45	13	43
23	12	21	11	19	15	25	10	28	14	43	14	47
24	11	22	11	20	15	26	10	28	13	41	11	51
25	12	21	11	21	15	27	10	27	12	39	11	53
26	12	20	11	20	14	26	11	26	11	40	11	54
27	12	20	13	20	14	28	12	26	11	41	10	52
28	11	20	14	19	13	28	13	26	12	42	11	48
29	11	19	15	18	12	28	14	25	14	42	12	44
30	11	19	15	18	12	31	14	25	12	43	12	39
31	10	20	15	19			14	27			12	38
Means . .	12·2	20·7	12·7	20·0	13·4	25·7	11·3	31·7	10·3	40·1	10·7	41·2

TABLE XXVI.

Smoothed Pressure Values for 1932—Atlantic Area.

		January.		February.		March.		April.		May.		June.	
		At.	P.R.	At.	P.R.	At.	P.R.	At.	P.R.	At.	P.R.	At.	P.R.
Pressures in Millibars – 1000.	1	12	34	15	41	17	31	13	32	17	22	16	17
	2	12	33	15	38	17	31	13	31	18	24	16	18
	3	11	33	14	36	16	35	13	31	20	25	16	18
	4	10	36	14	31	15	37	13	32	20	27	16	18
	5	9	39	14	29	15	40	13	34	20	29	16	19
	6	6	41	15	27	14	44	13	36	19	29	16	20
	7	4	42	16	26	14	46	13	38	19	28	16	21
	8	3	43	18	26	13	44	13	39	17	28	15	22
	9	2	43	19	27	12	41	13	38	15	28	15	22
	10	3	42	20	26	10	39	14	34	14	26	14	21
	11	4	44	19	29	9	36	14	31	13	26	13	20
	12	6	48	18	29	8	32	16	29	13	25	13	21
	13	7	51	16	28	8	31	17	28	13	22	14	23
	14	7	54	14	31	8	33	19	26	14	21	15	23
	15	7	56	13	37	9	31	19	27	15	21	16	23
	16	7	57	13	40	11	31	19	28	15	21	16	22
	17	8	55	13	44	12	30	18	28	16	21	17	19
	18	8	53	13	46	12	29	18	28	16	20	16	18
	19	10	52	14	44	14	27	17	27	16	20	16	17
	20	12	48	14	42	15	25	16	25	16	20	16	16
	21	14	45	14	40	14	24	16	25	16	19	16	16
	22	15	44	14	36	15	24	16	24	16	19	15	17
	23	17	43	13	33	15	25	15	26	17	20	15	18
	24	18	42	13	30	13	25	16	27	17	20	14	19
	25	18	42	14	29	12	28	15	27	17	19	14	18
	26	16	45	16	29	11	30	14	25	17	18	14	18
	27	15	46	17	29	11	32	13	25	17	17	12	17
	28	15	46	18	30	12	32	13	23	17	15	11	16
	29	14	46	18	30	13	32	13	21	16	14	10	16
	30	13	47			13	32	15	21	16	15	9	18
	31	15	44			13	33			16	16		
Means . .		10·3	44·9	15·3	33·2	12·7	32·6	15·0	28·8	16·4	21·8	14·6	19·0

TABLE XXVII.

Smoothed Pressure Values for 1932—Atlantic Area.

Pressures in Millibars — 1000.	July.		August.		September.		October.		November.		December.	
	At.	P.R.	At.	P.R.	At.	P.R.	At.	P.R.	At.	P.R.	At.	P.R.
1	9	19	11	21	11	27	13	24	14	25	9	46
2	10	21	11	21	10	29	13	24	15	25	8	40
3	11	22	12	20	9	31	13	23	15	27	8	35
4	11	21	12	19	9	29	12	24	15	28	9	31
5	12	21	12	18	9	28	13	26	15	28	10	28
6	12	21	12	18	8	26	13	28	15	27	11	23
7	12	22	13	17	8	25	12	29	15	29	13	23
8	12	21	13	17	8	24	12	29	15	29	15	27
9	13	20	13	15	8	26	12	29	15	29	15	29
10	14	19	13	15	8	29	11	28	15	31	15	30
11	15	17	13	13	8	31	11	28	16	35	15	31
12	15	16	13	13	10	30	11	28	17	34	14	34
13	15	17	14	14	11	31	10	29	17	34	13	36
14	14	17	15	15	13	30	11	29	17	34	11	41
15	14	18	15	17	15	25	9	32	17	32	8	48
16	14	20	15	19	16	23	9	33	16	27	6	54
17	14	21	16	20	16	24	8	32	14	29	5	54
18	14	21	16	21	16	26	9	32	13	31	4	53
19	15	22	16	21	15	26	8	33	12	31	4	50
20	15	22	16	20	14	27	9	29	10	36	7	45
21	14	22	16	20	13	28	9	28	9	38	9	41
22	15	21	16	19	13	28	10	29	8	41	11	40
23	14	19	15	19	12	28	10	28	8	39	12	40
24	14	18	15	19	12	27	10	29	8	39	13	41
25	14	17	15	20	12	28	11	28	9	36	12	42
26	14	16	14	19	12	29	11	28	11	38	11	44
27	13	16	13	20	12	28	12	27	11	39	10	45
28	13	15	12	20	13	26	12	27	11	43	8	46
29	12	16	11	21	13	26	12	25	11	42	6	47
30	12	18	11	22	13	25	13	26	10	43		
31	12	19	10	25			14	25				
Means . .	13·2	19·2	13·5	18·6	11·6	27·4	11·1	28·3	13·2	33·2	10·0	39·7

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F

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